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LOW COST, WIDE ANGLE INFINITY OPTICS VISUAL SYSTEM.(U)

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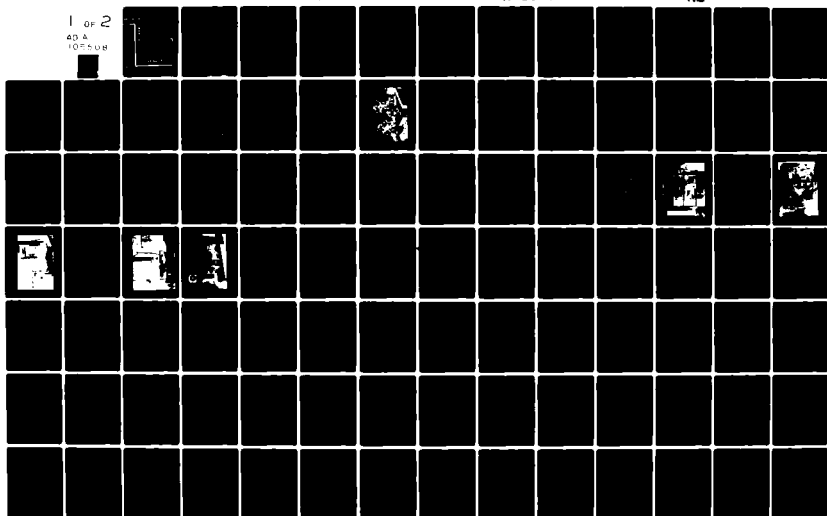
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LOW COST, WIDE ANGLE INFINITY
OPTICS VISUAL SYSTEM

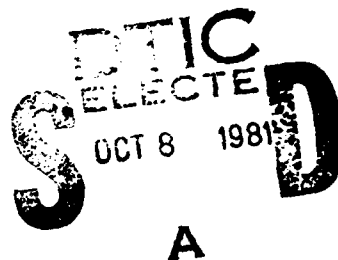
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Final Report



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Prior to the production of these holograms, holographic research was carried out to investigate and resolve problems which have affected the quality and the repeatability of the final product. Specific attention was given to holographic ghost images which seriously impaired the contrast and the resolution of the images produced by the holographic Pancake Window and to the effects of environmental controls. The final production of the holographic beamsplitter was delayed by a stability problem in the wet cell used to support the holographic plate during the holographic exposure.

The phosphors in the CRT displays were originally designed to be P-44 narrow band phosphors but were later changed to a wide-band emission phosphor. The reason for this was a wavelength peak response shift of the holograms with large field-of-view angles. The use of a wide-band phosphor, although it penalized the transmission of the holographic Pancake Window, required less stringent wavelength peak location in the manufacture of these holographic beamsplitter mirrors. <

The optical performance of these windows proved the feasibility of the holographic optical elements. As compared with a classical Pancake Window system in which classical glass mirrors are used, the performance of these holographic windows was inferior, not because of inherent limitations, but because of cosmetics, uniformity, and hologram quality which could be improved with present technology.

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SUMMARY

Objective

The objective of this effort was the design and development of a dynamic wide angle visual display system consisting of a mosaic of three Holographic Pancake Windows (HPWs), cathode ray tubes (CRTs), and camera/model image generator integrated with a digital computer for aircraft dynamics generation and control.

Background

The HPW system is a standard Pancake Window system in which the very heavy and expensive glass-spherical beamsplitter mirror is replaced by a holographic analog. This holographic spherical mirror analog is produced holographically (photographically) in a very thin and flat gelatine film. The holographic mirror works not by reflection but by diffraction and, consequently, is not physically spherical but flat. This property permits the HPW to be assembled in a single unique package with all of its elements cemented together. In the classical Pancake Window, three separate elements are required due to the curvature of the spherical mirror.

The Pancake Window consists of two linear polarizers, two quarter wave plates, and two beamsplitter mirrors. One of the beamsplitters is a spherical beamsplitter whose focal plane is folded by the other beamsplitter which is a plane beamsplitter. Light that originates in the focal plane of the spherical beamsplitter becomes collimated upon reflection on the beamsplitters. Thus, if a picture of the real world is placed at the focal plane of the spherical mirror, an observer viewing through the window will see the information of the picture at optical infinity as in the real world but will not see the picture directly. The Pancake Window, therefore, is operating as an on-axis, in-line magnifier lens. Multiple Pancake Window units can be butted together and can potentially produce a 360° field-of-view system. At the Air Force Human Resources Laboratory, a dodecahedron configuration using pentagonally shaped Pancake Window systems has been used in the Advanced Simulator for Pilot Training (ASPT) and in the Simulator for Air-to-Air Combat (SAAC). In specific applications, holographic optical elements should compete favorably with conventional lenses and mirrors and, in the Pancake Window configuration, a holographic spherical beamsplitter should significantly reduce the production cost and the weight of the total system.

Approach

The approach involved a number of sequential and parallel activities. For example, to evaluate the optical performance of the holographic optical elements, a 17-inch diameter holographic spherical beamsplitter mirror was produced and assembled in the Pancake Window configuration. The performance of a high powered Argon laser for holographic production and related techniques and facilities was also evaluated and tested during this program. There was also a continued holographic development effort to improve the quality and repeatability of the holograms as a consequence of what was learned in the 17-inch HPW development. The individual windows were configured in a mosaic of three units butted edge by edge and with a dynamic imagery display generated by a T.V. model board. The mosaic display was then integrated with a simulator cockpit and associated computers. The performance of the display was evaluated as part of the total visual flight simulation system.

Specifics

Prior to the production of the Holographic Spherical Beamsplitter (HSBS) mirror, R&D was carried out to investigate and resolve problems that have affected the quality and the repeatability of the final

product. Specific attention was given to holographic ghost images which seriously impaired the contrast and the resolution of the images produced by the HPW and to the effects of environmental controls. The final production of the holographic beamsplitter was delayed by a stability problem in the wet cell used to support the holographic plate during the holographic exposure. The phosphors in the CRT displays were originally designed to be P-44 narrow-band phosphors but were later changed to a wide-band emission phosphor. The reason for this was a wavelength peak response shift of the holograms with large field-of-view angles. The use of a wide-band phosphor, although it penalized the transmission of the HPW, required less stringent wavelength peak location in the manufacture of these holographic beamsplitter mirrors. At the conclusion of installation, alignment and testing of the three window display system, several defects became apparent. The most obvious defect was that there was too little overlap of the views across the window seams. Even though the test data confirmed that there was indeed a 5-degree overlap, very slight head motions exposed the dark or non-image areas between windows. The second most noticeable fault had to do with image quality; namely, brightness and resolution. During system testing, it was proved that the cameras provided high resolution video. The problem was, therefore, in the CRT projection system. The loss of resolution was attributable to the reduction in video bandwidth of the display system, which resulted from damaged drive electronics. The brightness deficiency occurred because of failure of the tube manufacturer to meet brightness specifications. Despite these faults, the fundamental feasibility and general performance of the three HPWs in a mosaic dynamic display configuration was demonstrated.

Conclusions/Recommendations

The optical performance of the HPWs in this study demonstrated the feasibility of the holographic optical elements, even though the performance of these particular windows was inferior to that of a classical Pancake Window system in which conventional glass mirrors are used. The inferiority observed was not the result of inherent technical limitations, but was rather due to deficiencies in cosmetics, uniformity, and hologram quality that could be improved with current technology. Therefore, it is recommended that the HPWs used in this study be replaced with the installation of three new windows, each peaked to the same desired reconstruction wavelength, and having identical focal lengths of 18.1 inches and optical centers on the geometrical axis of the display. This modification should produce marked improvements in system performance.

PREFACE

This study was conducted by the Operations Training Division, Air Force Human Resources Laboratory, Air Force Systems Command. The study supports Project 1958 Training Simulation Technology Integration: George J. Dickison and Warren E. Richeson, project monitor; Task 195801, Advanced Visual Systems, Arthur T. Gill and Eric G. Monroe, task scientist; and 19580101, Holographic Pancake Window Development, Arthur T. Gill and Eric G. Monroe, work unit monitor. The project engineer responsible for the program and assembly of the complete system was initially Robert Plummer and throughout the final part of the program Ted Lenczowski. The holographic research, development design of new holographic facilities and manufacturing of the Holographic Pancake Windows was directed and carried out by Jose R. Magarinos with the collaboration of Daniel Coleman and the technical assistance of Ray LaRussa and John Andres. Contributors to this program were Martin Shenker as chief of optical design and Edward Rossi and Joseph LaRussa as consultants. The final assembly and testing was carried out by Frank Wong and Frank Hom under the supervision of John Lense as optical engineer and Ted Lenczowski as project engineer.

The purpose of this contractual effort was to demonstrate the engineering feasibility of ultimately developing large holographic beamsplitter analogs to the current classical Pancake Windows utilizing beamsplitter spherical mirrors. Classical windows currently used as the infinity optics in the optical mosaic displays utilized in flight simulators such as the Advanced Simulator for Pilot Testing (ASPT) and Simulator for Air-to-Air Combat (SAAC) are both heavy and costly. Hopefully, the holographic analog would provide savings in both weight and cost. The weight saving is important in simulators employing platform motion. Cost factor is significant in large scale visual weapon systems trainers (WST) procurement utilizing optical mosaic displays.

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LOW COST, WIDE ANGLE INFINITY-OPTICS

VISUAL SYSTEM

Abstract

Holographic beamsplitter spherical mirrors have been introduced in the Pancake Window visual simulators as a low-cost and low-weight substitute for the classical glass beamsplitter spherical mirrors. The goal of this project was the production of a three-channel visual simulator consisting of a mosaic of three holographic Pancake Windows in which these beamsplitter spherical mirrors are used. The field-of-view of the complete display is 45° vertical and 140° horizontal and will be used to demonstrate a dynamic, unprogrammed visual simulation imagery generated by T.V. camera/model and gantry image generator.

Prior to the production of these holograms, holographic research was carried out to investigate and resolve problems which have affected the quality and the repeatability of the final product. Specific attention was given to holographic ghost images which seriously impaired the contrast and the resolution of the images produced by the holographic Pancake Window and to the effects of environmental controls. The final production of the holographic beamsplitter was delayed by a stability problem in the wet cell used to support the holographic plate during the holographic exposure.

The phosphors in the CRT displays were originally designed to be P-44 narrow band phosphors but were later changed to a wide-band emission phosphor. The reason for this was a wavelength peak response shift of the holograms with large field-of-view angles. The use of a wide-band phosphor, although it penalized the transmission of the holographic Pancake Window, required less stringent wavelength peak location in the manufacture of these holographic beamsplitter mirrors.

The optical performance of these windows proved the feasibility of the holographic optical elements. As compared with a classical Pancake Window system in which classical glass mirrors are used, the performance of these holographic windows was inferior, not because of inherent limitations, but because of cosmetics, uniformity, and hologram quality which could be improved with present technology.

SECTION I

Introduction

This report describes an effort to design and develop a dynamic visual display consisting of a mosaic of three Holographic Pancake Window* (HPW) displays, CRTs, and electronics, as well as a peripheral T.V. camera/model image generator, and its integration with a digital computer for aircraft dynamics generation and control. The objective of this project is to test the performance of the HPWs when assembled in a mosaic configuration (butted together to provide very large field-of-view angles) and under a dynamic visual input.

The HPW is an in-line infinity visual display system in which the spherical beamsplitter mirror used in the classical Pancake Window display counterpart has been replaced by a holographic analog. The introduction of the holographic mirror may reduce the manufacturing cost by 75% and also the weight of the Pancake Window system by 75%.

Prior to this project, a 17-inch-diameter HPW was produced and evaluated. It was found that the imagery was degraded by ghost images and by a loss of contrast and resolution, particularly when viewed on-axis. To resolve the problem, an investigation and improvement of holographic technology was undertaken before the production of the three HPWs began.

Classical Pancake Window Theory. Experience in producing optical simulators led to the development of the Pancake Window display, an in-line, compact, infinity display system with the advantages of using only reflective optics and providing very large field-of-view angles.

The Pancake Window display consists of two linear polarizers, two quarter-wave plates, and two beamsplitter mirrors arranged as illustrated (Figure 1). Each linear polarizer with its adjacent quarter wave plate forms a circular polarizer. One of the beamsplitters is spherical

*Pancake Window^R is a registered trademark of Farrand Optical Co., Inc.

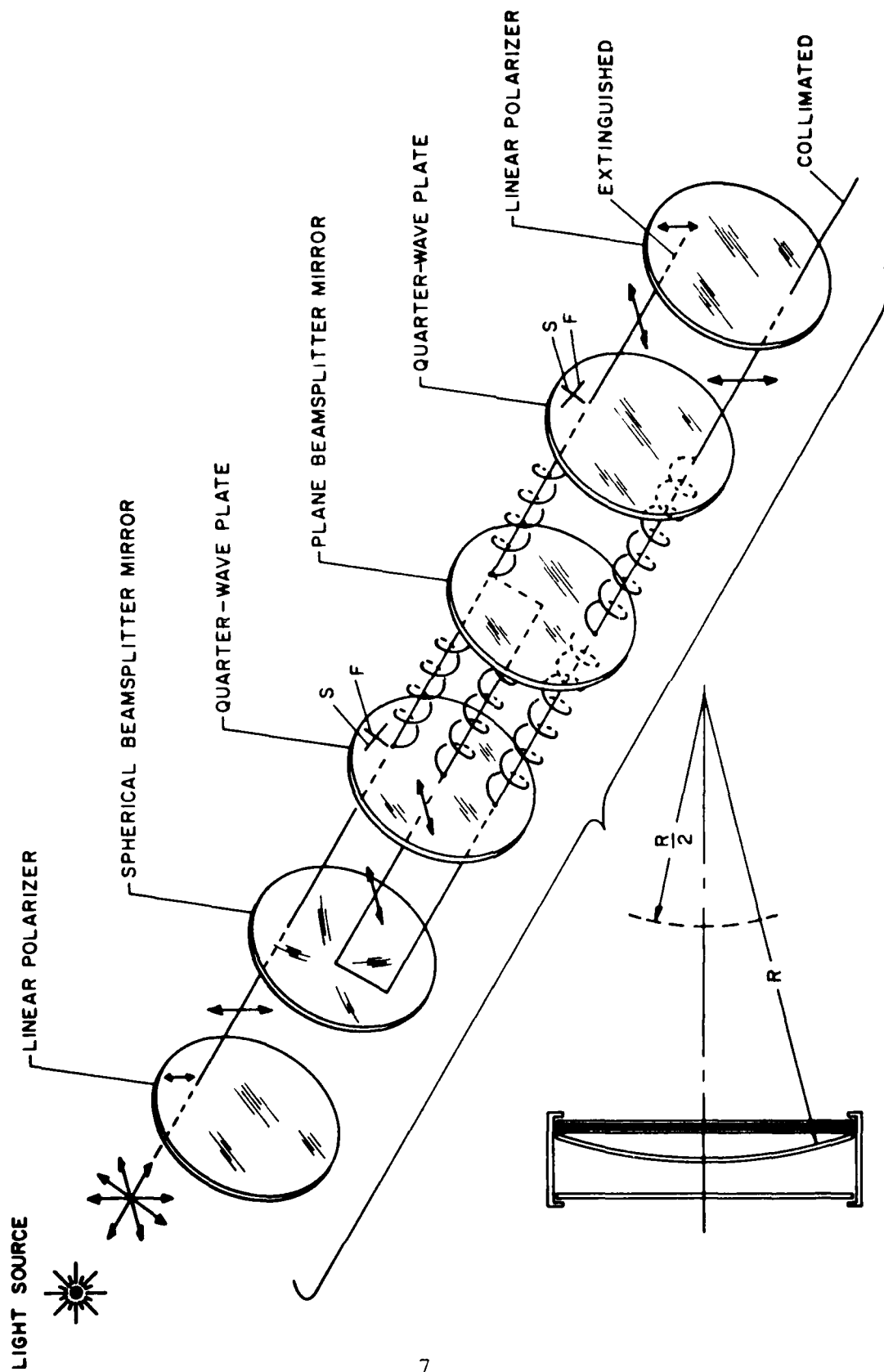


FIGURE 1. PANCAKE WINDOW CONFIGURATION

and has a focal plane that is folded by the other plane beamsplitter. Light that originates in the focal plane of the spherical beamsplitter becomes collimated upon reflection on both beamsplitters, consequently, the information displayed at the focal plane will be displayed at optical infinity when viewed through the Pancake Window. Because it uses beamsplitter mirrors, part of the light may be transmitted through the Pancake Window without being reflected by the beamsplitter mirrors.

To avoid the direct transmission of the light, the Pancake Window uses a system of linear polarizers and quarter-wave plates, (Figure 1). Unpolarized light reaching the Pancake Window becomes linearly polarized when passing through the first element, a linear polarizer. The light passes through the spherical beamsplitter and then through the first quarter-wave plate, causing it to become circularly polarized. It will be partially transmitted and partially reflected in the plane beamsplitter mirror. Transmitted light becomes linearly polarized again going through the second quarter-wave plate and is "crossed" or absorbed by the last element, the second polarizer whose axis is rotated 90° with respect to the first linear polarizer. Reflected light in the plane beamsplitter, being circular, suffers a change in handedness upon reflection, and when it becomes linear after passing again through the first quarter-wave plate, it has its plane of polarization rotated 90° with respect to the light that was transmitted. Upon being reflected again at the spherical beamsplitter, the light reaches the last polarizer with its plane of polarization not crossed but parallel to its linear axis: consequently, this light will be transmitted by the Pancake Window display.

If a picture of the real world is placed at the focal plane of the spherical mirror, an observer viewing through the window will see the information of the picture at the optical infinity as should be in the real world but will not see the picture directly. The Pancake Window display is operating then as an on-axis, in-line magnifier lens, and acts as a reflective rather than a refractive system. This will permit very fast systems to be designed which is practically impossible using refractive optics.

A typical Pancake Window display has the following characteristics:

1. An eye relief of 29" for an 84° instantaneous field-of-view allowing 12" of head motion ("pupil" size)

around the center of curvature of a 48" radius mirror.

2. The focal length is 24" and the overall thickness under 12".
3. Maximum decollimation would be 9 arc minutes over any head motion and field angle.
4. No color errors or geometric distortion over an 34° instantaneous field where the only significant aberration is the spherical aberration.

Multiple Pancake Window display units can be butted together and can potentially produce a 360° field-of-view system. A dodecahedron configuration using pentagonally shaped Pancake Window displays has been used in the U.S. Air Force Advanced Simulator for Pilot Training (ASPT) and Simulator for Air-to-Air Combat (SAAC). The all-around vision capability and size of the ASPT system is shown in (Figure 2).

Holographic Pancake Window Theory. The HPW system is a standard Pancake Window system in which the very heavy and expensive glass spherical beamsplitter mirror is replaced by a holographic analog. This holographic spherical mirror analog is produced holographically (photo-graphically) in a very thin and flat gelatin film. The holographic mirror works not by reflection but by diffraction and, consequently, is not physically spherical but flat. This property permits the HPW to be assembled in a single unique package, all of its elements being cemented together. In the classical Pancake Window three separate elements are required due to the curvature of the spherical mirror (Figure 3).

One of the drawbacks of using holographic optical elements is that the substrate that supports the holographic films produces unwanted reflections. These reflections, being usually of different magnification, deteriorate and interfere with the viewing of the principal image. This effect does not happen in the Pancake Window configuration in which the holographic substrate is optically cemented (with an index of refraction match) and the circular polarizer configuration eliminates surface reflection.

A particular characteristic of the HPW is that its spectral response corresponds to the spectral response of

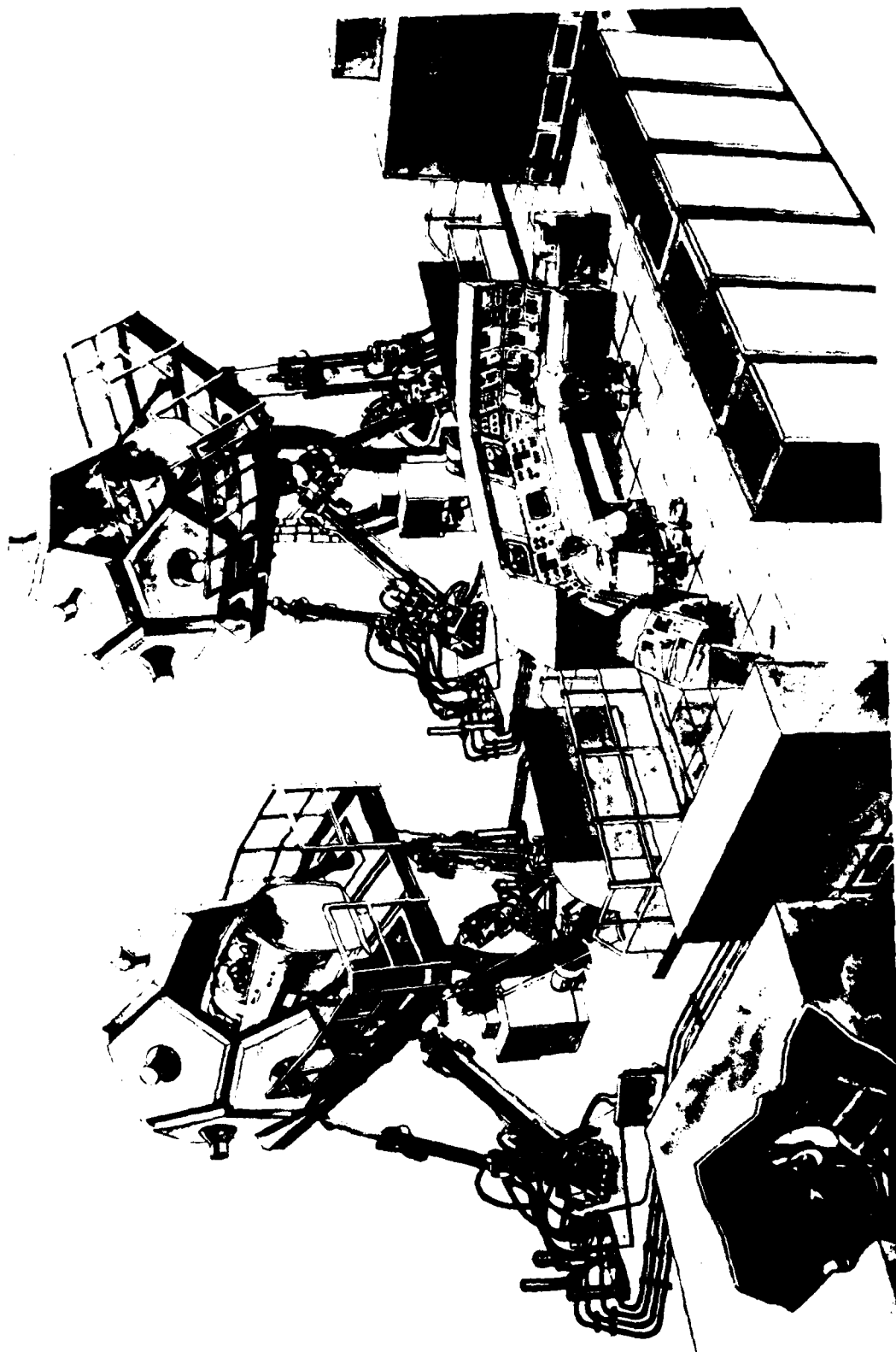


FIGURE 2. ASPT SYSTEM

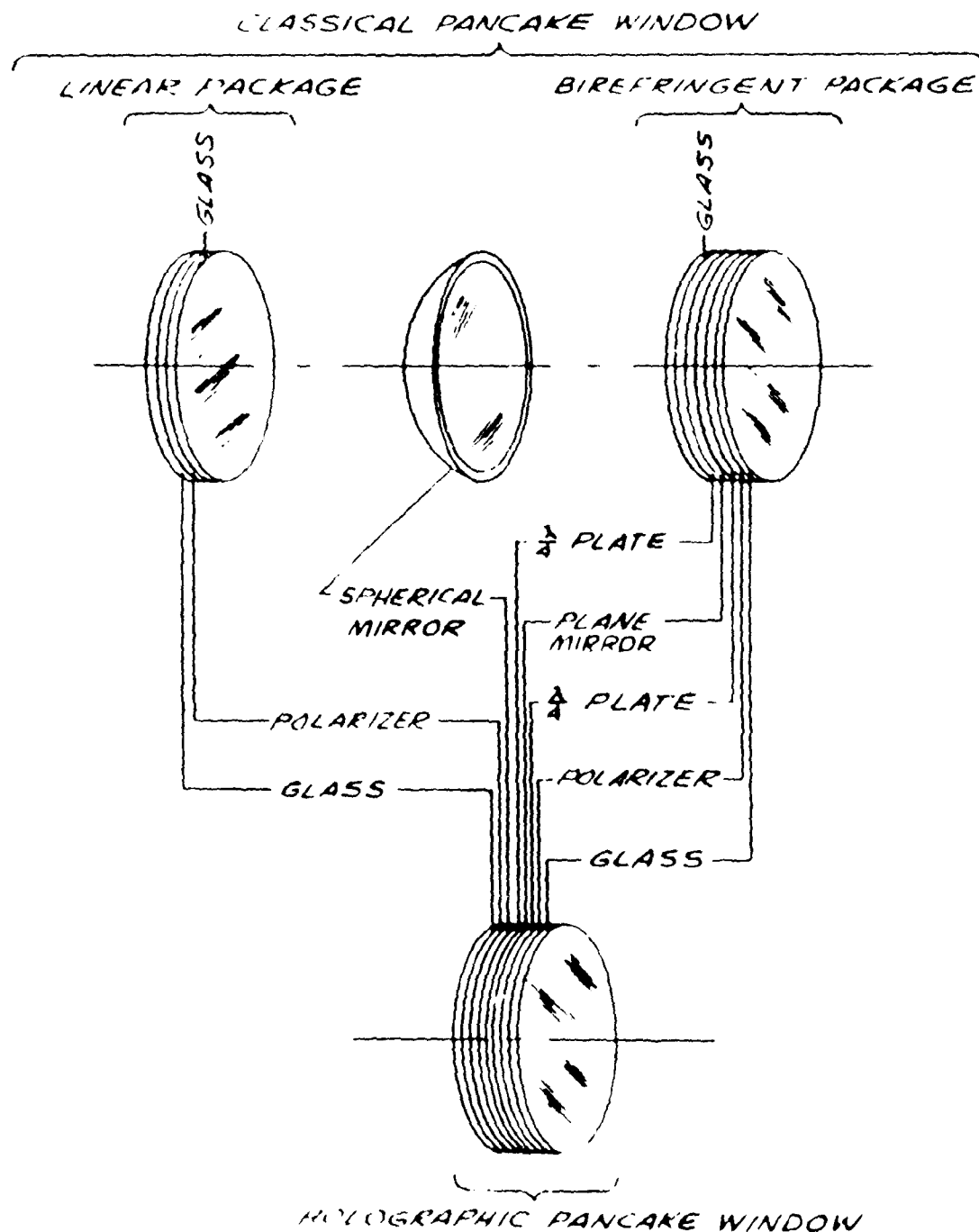


FIGURE 3. HOLOGRAPHIC Vs CLASSICAL
PANCAKE WINDOW PACKAGE

the holographic spherical beamsplitter. The holographic mirrors developed in this program were monochromatic and were produced to match the spectral response peak of the CRT phosphor.

Holographic Spherical Beamsplitter Theory. A hologram is the recording of the intensity and phase characteristics of two wavefronts of radiation. These are recorded as intensity variations of the pattern produced by the interference of the wavefronts at the recording plane. After being processed, and if properly illuminated, the hologram will reproduce the original wavefronts by a process of diffraction.

The holographic recording material can be modulated only at the surface (plane holograms), or throughout its volume (volume holograms), and can be phase modulated or absorption modulated.

The holograms used in the holographical spherical beamsplitter mirrors (HSBS) are of the volume-phase type. The material to record these holograms is a gelatin film hardened to the point in which it just becomes insoluble in water at normal room temperature. The film is photosensitized with ammonium dichromate and upon exposure to light becomes slightly harder in areas where the absorption of the light was greater. After the photosensitized dye is washed out the film is swelled with water and then is rapidly dehydrated. The dehydration and drying create strain areas and material modifications in the volume of the film with local changes in its index of refraction. This index of refraction modulation produces a three-dimensional diffraction grating which is the hologram.

To produce holographically a mirror, the film in which the hologram is recorded should be illuminated by two wavefronts, each originating in point sources coincident with its focus. Since a sphere has the two foci coincident in its center of curvature, two wavefronts are used, one emanating and the other converging at the same point which will become the center of curvature of the holographic spherical mirrors (Figure 4). When the holographic mirror is illuminated, it will diffract light. The diffracted wavefront will have similar characteristics to those of a reflected wavefront from a classical mirror. If the hologram diffracts all of the incident light, it will be equivalent to a total reflecting mirror. If only part of the light is diffracted by the holographic mirror, it will be equivalent to a partially reflecting mirror or a beamsplitter mirror.

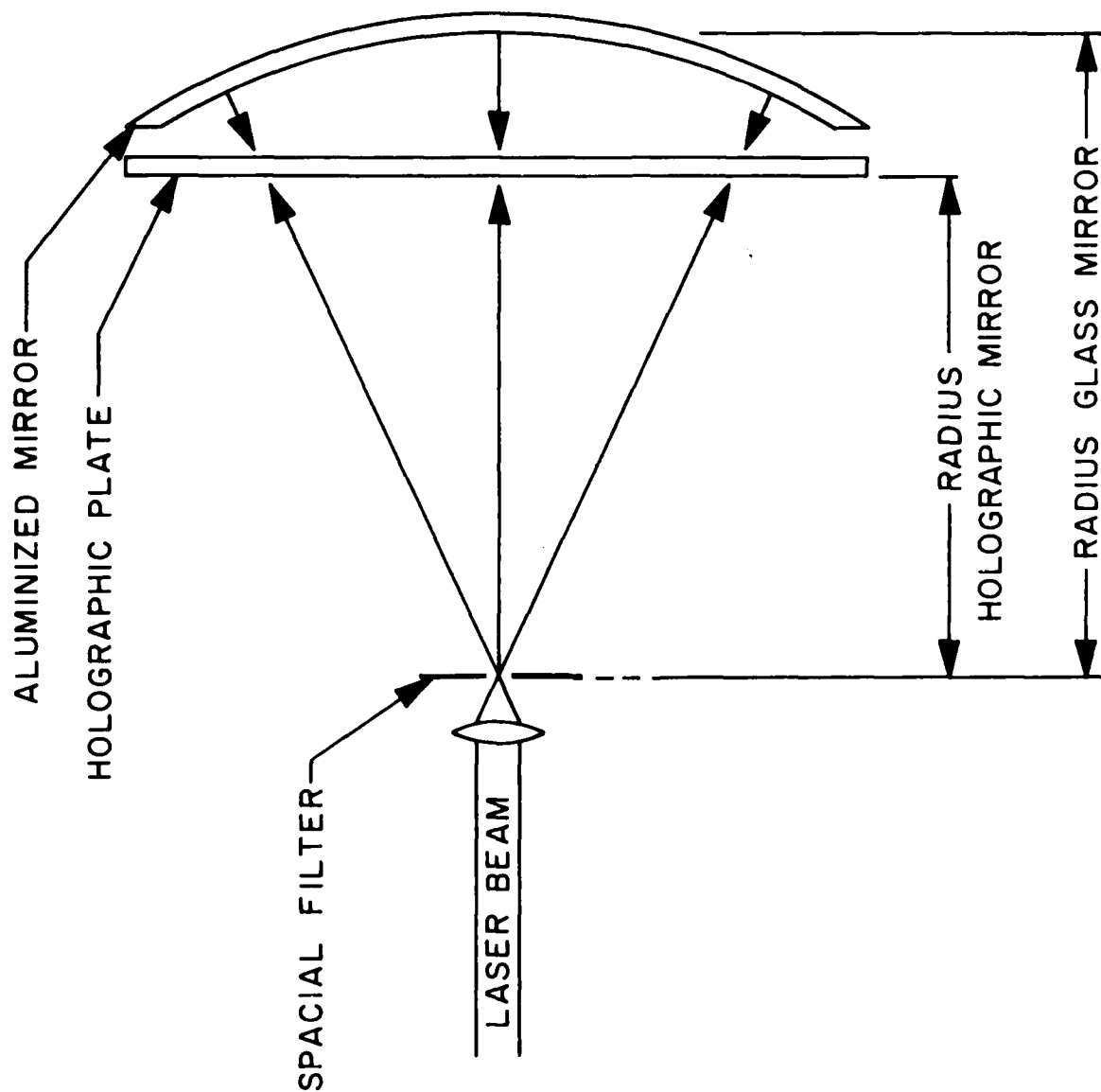


FIGURE 4. HOLOGRAPHIC SPHERICAL BEAMSPLITTER
CONSTRUCTION GEOMETRY

Project Evaluation

In specific applications, holographic optical elements, (HOEs) could compete favorably with lenses and mirrors. Also, as mentioned before, in the Pancake Window configuration a holographic spherical beamsplitter could reduce drastically the production cost and the weight of the system.

A breakthrough achieved in the HOE field was the production of holographic films whose overall characteristics were more desirable than the ones commercially available. The development of these films (ammonium dichromate photosensitized gelatin type film) led to the production of volume-phase holograms with a diffraction efficiency close to 100% and no observable scattering. The capability of producing film of any size also eliminated the restriction imposed on size by the commercially available films.

To evaluate the optical performance of the holographic optical elements, specifically, the holographic beamsplitter mirrors which could be used in the Pancake Window display, a 17"-diameter holographic spherical beamsplitter mirror was produced and assembled in the Pancake Window configuration. The performance of a high power continuous wave (cw) argon laser for holographic production and related techniques and facilities, was also evaluated and tested, together with this effort.

As a further step in the evaluation of the HPW, the windows were evaluated, not as single units but in a mosaic of three units butted edge by edge and with a dynamic imagery display. There was also a continued holographic development effort to improve the quality and repeatability of the holograms as a consequence of what was learned in the 17" HPW development.

Prior Project Analysis

The performance of the 17" HPW pointed out a series of defects and inconsistent results which required further research. Consequently, an in-depth analysis was started which concentrated particularly on two areas: origin and possible elimination of ghost images, and influence of environmental parameters in the quality and repeatability of the hologram production.

Report Contents

The content of the remaining sections is as follows:

Section II deals with analysis and problem identification of the 17" HPW. Solutions are proposed and a statement is made of the need of further holographic development and better holographic facilities prior to the production of the three HPWs. Section III describes the new holographic facilities, their justification and specifications. Section IV contains the additional holographic development with descriptions of the experiments carried out and the results of these experiments. Section V relates to the manufacture of the three holographic spherical beamsplitter mirrors (HSBM) and specific problems which arose in this effort. Section VI covers the production and assembly of the three holographic windows. Spectral response problems are considered, and the change of the CRT phosphor is discussed. Section VII contains the performance and evaluation data of the three butted HPWs. Section VIII recommends possible modifications for the improvement of the HPW. Section IX contains a description of the complete visual simulator system. Section X describes the performance of the complete system with respect to contract specifications. Section XI gives suggestions and recommendations for improvement of the complete system.

SECTION II

17"-HOLOGRAPHIC PANCAKE WINDOW:

ANALYSIS AND EVALUATION

As part of an earlier effort, a "holographic, volume-phase 17" aperture, on-axis, spherical beamsplitter mirror" was developed (AFHRL-TR-78-29). The 17" holographic mirror was only visually analyzed prior to being assembled in the HPW configuration. An Air Force resolution chart was observed by reflection, and deterioration was not noticeable in the resolution when the observation was made side by side with a classical mirror. Also, the resolution was the same on-axis and at $+20^{\circ}$ off-axis. Local variation was attributed to local hologram defects or non-uniformities. The diffraction efficiency (reflection) was not measured, but by comparison with other holograms that have been measured, it was estimated higher than 70%. Scattering was not visually detectable, and in general, the visual performance was judged to be quite acceptable.

The lack of a room which had humidity and temperature controls prevented better analyses. The concern was with the possibility that the holographic mirror might be destroyed or deteriorated if it was handled in an environmentally uncontrolled room before cementing.

The diffraction efficiency vs. wavelength of a holographic spherical beamsplitter mirror (HSBM) similar to the one used in the delivered 17" HPW is shown in Table 1.

The 17" HPW was assembled in a single package and had the standard materials used in the classical Pancake Window. Two exceptions were the holographic beamsplitter mirror which replaces the classical spherical beamsplitter and the elimination of two cover or end plates as a consequence of a single package assembly (Figure 3).

The visual analysis of this 17" HPW revealed noticeable deterioration of performance. The most disturbing effect was a loss of contrast and resolution when the HPW was used on-axis. When the HPW was tilted, or the image

Table 1. HOLOGRAPHIC BEAMSPLITTER
DIFFRACTION EFFICIENCY

<u>Wavelength</u> <u>(nanometers)</u>	<u>Efficiency Diffraction</u> <u>Percent</u>
520	1.14
530	5.0
540	6.0
550	41.0
560	81.0
570	34.0
580	19.0

was observed at large off-axis angles, the resolution and the contrast performance were improved. Also disturbing was a new ghost image, a very bright real image, which was formed very close to the observer's eye position.

The transmission of the HPW did not depart greatly from the expected values. With a monochromatic source peaked at 562nm, the transmission was 0.8%, and with a broad band fluorescent source, the transmission was naturally much lower (0.17%) due to the narrower peak response of the holograms. The ghost images, photometrically measured, were very much brighter than the corresponding ones in the classical Pancake Window.

At this stage, prior to an in-depth analysis, it was hypothesized that the deterioration in performance of the HPW was caused by a new ghost image and poor quality of the holographic mirror in spite of the fact that the holographic mirror by itself was judged acceptable. This was understandable since the holographic mirror in the Pancake Window configuration works as a beamsplitter (by reflection and by transmission).

Possible causes of the new ghost images are as follows: (a) the hologram was working as a mirror and as a lens; (b) images were formed by multiple orders of diffraction; and (c) multiple hologram registration was caused by secondary reflections in the construction geometry.

Possible causes of the poor quality of the hologram are the lack of flatness of the gelatin film and non-uniformity across the holographic area due to uneven film thickness and/or uneven hardness.

Identification of Problems

New Ghost Images. To identify the problem and origin of the new and/or brighter ghost images, a 17" HPW was assembled, not as a cemented single package, but as a triple package, similar to the classical system (Figure 3). The identification and formation of each ghost were verified by tilting or changing the separation of the three packages, which displaced the position of the ghosts. These ghosts were compared with the ones produced by the classical window, and it was found that the new ghosts were superimposed or formed very close to the classical ghosts. The 17" HPW, consequently, has a series of families of ghost images, each family corresponding to each single

ghost image in the classical system (Figure 5).

The hypothesis of the hologram working also as a lens agrees with the number and the location of the new ghosts, but has the theoretical inconsistency of forming images with no appreciable dispersion (typical of reflection and not transmission-lens holograms) and, transmitting them when the system should suppress the direct transmission of light.

A possible reflection between the holographic spherical mirror and its flat substrate as being the cause of this so-called "lenticular image" was also tested. High efficiency antireflection (AR) coated glass and/or a thick slab of glass was cemented to the glass substrate, but no change in brightness or location of the "lenticular ghost" was observable.

Finally the possibility of a double hologram registration was theorized: one hologram being a spherical beamsplitter and the other a plane beamsplitter produced by internal reflection on the glass substrate during the construction of the hologram. To test this hypothesis, a hologram was constructed using a wet cell. This is a cell which is formed with high efficiency AR coated glass and is filled with a liquid which matches the index of refraction of the glass substrate. The hologram, during construction, is immersed in the wet cell and the internal reflections are eliminated.

A hologram constructed with a wet cell was assembled in the Pancake Window geometry and tested for the "lenticular" or new holographic ghost images. This system did not have the extra ghost images and only the ghost images of the classical system were observed.

It was found, consequently, that the new holographic ghost images were caused by a double holographic registration and could be eliminated using a wet cell in the hologram construction geometry.

Loss of Contrast and Resolution. The cause of the loss of contrast and resolution could not be initially determined in the 17" HPW system, especially when used on-axis. It was finally determined that this loss of performance was observed with most of the holograms which were assembled in the Pancake Window configuration but not with all of the holograms. Also there was no noticeable difference in quality when the holograms which produced good resolution performance and the ones which caused

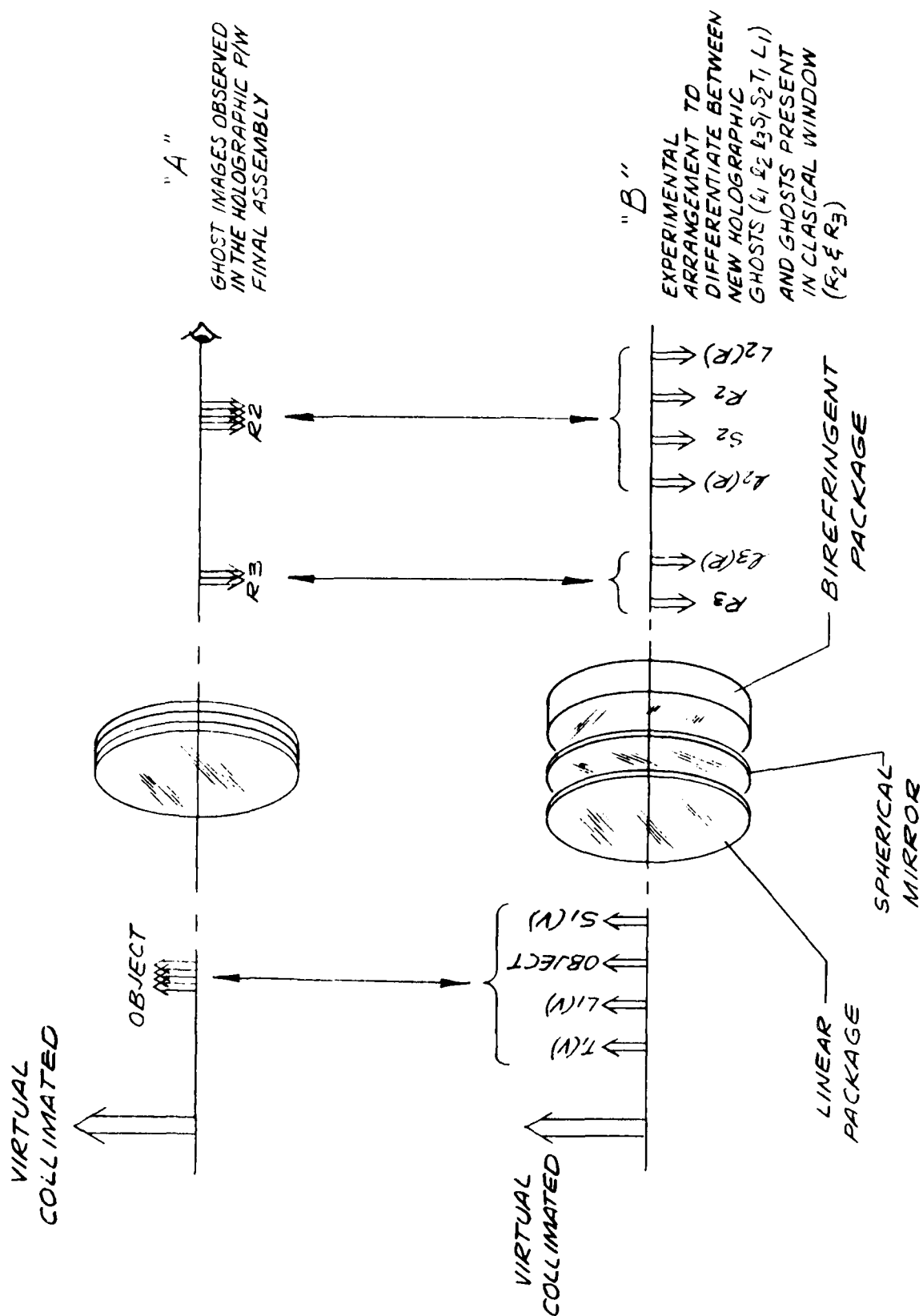


FIGURE 5. 17-INCH HOLOGRAPHIC PANCAKE LITHOLOGY GHOST IMAGE

deterioration in resolution were visually examined as holographic mirrors and not in the Pancake Window configuration.

In attempting to differentiate between the holographic mirrors which give good HPW resolution and the ones which give poor HPW resolution, no meaningful correlation could be established, because the parameters of construction of the holograms were not constant and adequate facilities to control them were not available. This lack of control was also responsible for poor repeatability of the results.

In general, the resolution was affected by the characteristics of the holographic film and a lack of environmental control in the holographic facilities. However, the principal reason for loss of on-axis performance of the HPW was different and was related to the relatively narrow spectral response of the hologram, coupled with the Pancake Window system characteristics.

The transmission of the Pancake Window system is a function of the reflectances of the spherical and the plane beamsplitter.

$$T = t_s \times t_p \times r_s \times r_p \times p$$

Where t_s = Transmission of the spherical beamsplitter
 r_s = Reflection of the spherical beamsplitter
 t_p = Transmission of the plane beamsplitter
 r_p = Reflection of the plane beamsplitter
 p = Transmission of the polarizers for parallel configuration

Without considering absorption, the maximum value for T is reached for values of 50% for the transmissions and the reflections. If these values are lower or higher, the transmission of the Pancake Window will be smaller. For a classical beamsplitter in which the spectral response is flat or very wide, this effect will not cause a variation in the transmission. For the holographic beamsplitter, which has a narrow spectral response, this effect could cause two peaks of maximum HPW transmission (two images) for the 50% holographic mirror reflection values if its maximum reflectivity is higher than 50%.

The reflection or diffraction efficiency values of the holographic beamsplitter used to manufacture the 17" holographic window, showed a value of 81% at 560nm and values of 50% approximately at values of 555nm and 565nm. The window consequently will have, not a maximum transmission at 560nm where the hologram peaks, but a maximum

at 555nm and another maximum at 565nm (Figure 6).

The transmission of the HPW will not have two maxima for large off-axis angles or when the window is tilted, due to a lower diffraction efficiency (reflection) of the hologram. At diffraction efficiency values closer to, or lower than 50%, the two transmission maxima will become coincident and will produce a single image and not a double image.

The fall of diffraction efficiency at very large off-axis angles corresponds to a deviation from the Bragg angle reconstruction. During the holographic construction of the mirror, the object (point source) is placed at a point corresponding to the center of curvature of the mirror (Figure 4). During the holographic reconstruction, the object is placed at half the distance (focus of the mirrors); consequently, the angular deviation between construction and reconstruction could become severe at large off-axis angles.

It was also verified that the real difference between the holograms which will produce good or bad on-axis resolution in the HPW was the reflection values. The bad ones were all those which have much higher diffraction efficiency than 50 percent.

Problem Solution

Once the problems affecting the performance of the 17" HPW were identified, the following solutions were proposed.

Holographic Ghost Images. These images will be eliminated if the HSBM mirrors are constructed using a wet cell which will suppress unwanted internal reflections with the substrate of the hologram.

On-Axis Resolution and Contrast. The diffraction efficiency of the holographic beamsplitter should be controlled so as not to exceed the value of 50%. Values smaller than 50% will lower the transmission of the Pancake Window. Values larger than 50% not only will lower the transmission of the window but will produce a doubling of the images with the consequent loss of contrast and resolution.

Uniformity and Repeatability. The characteristics of the holographic film will affect the quality and

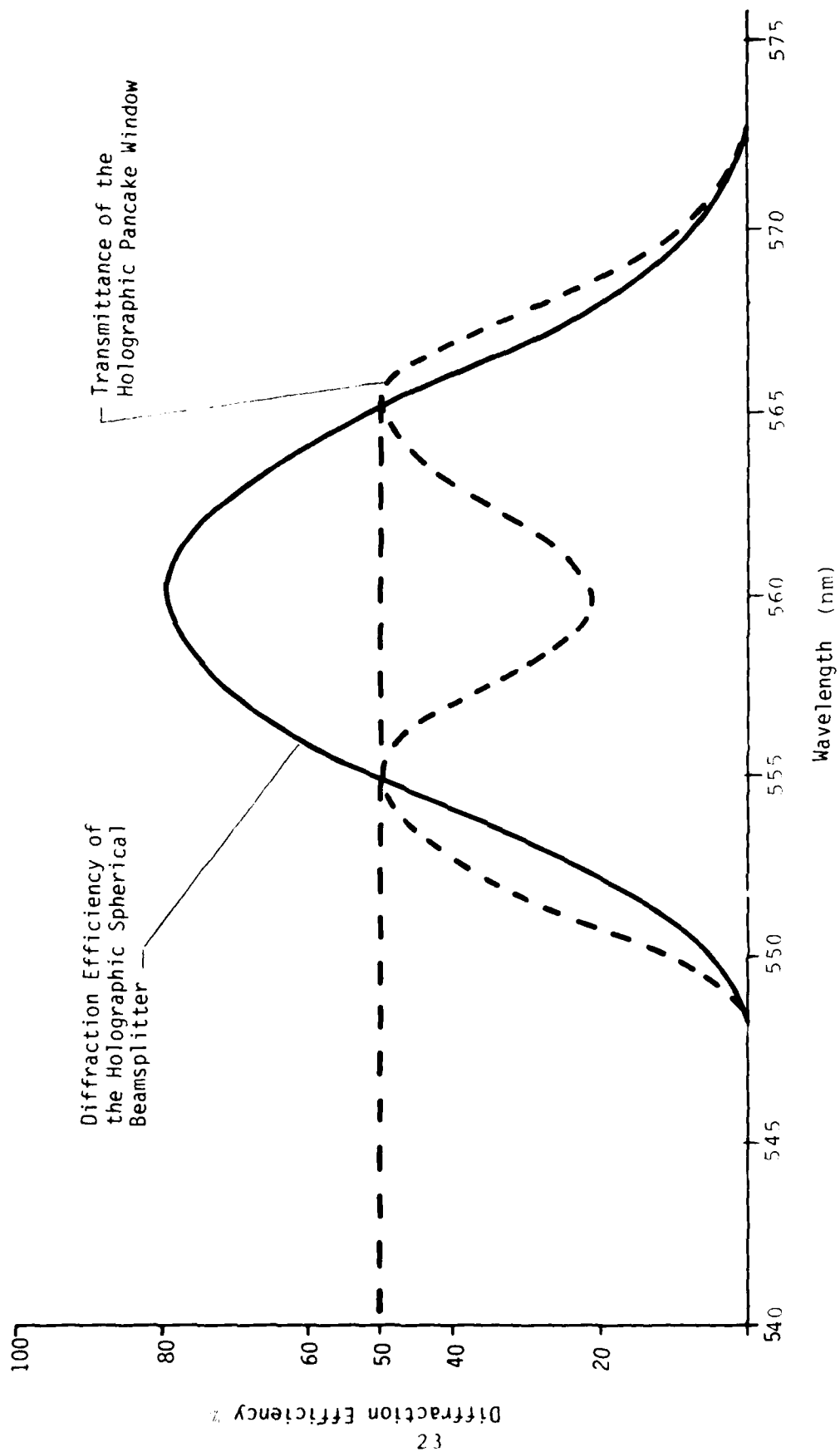


FIGURE 6. 17-INCH HOLOGRAPHIC PANCAKE WINDOW
DOUBLE WAVELENGTH PEAK TRANSMISSION

performance of the hologram. It is most important to determine the relative influence of each holographic parameter related to the final product and have the means of controlling this parameter. Further research and development was conducted specifically in the areas of: (a) flatness and uniformity of the gelatin film; (b) hardness of the gelatin film; (c) influence of environmental parameters on product repeatability.

SECTION III

NEW HOLOGRAPHIC FACILITIES

Justification for New Facilities

As a result of the analysis of the performance of the 17" HPW, a need for better holographic facilities was established and it was proposed and implemented before the development of the three 32" diameter holographic beamsplitter mirrors were initiated. The objective of the new facility was to provide a controlled environment in which the importance of various parameters could be established independent of each other and would maximize the quality and the repeatability of the holograms.

The rooms were designed specifically for holographic work and are capable of producing the 24" by 21.5" holograms. They were custom-made and every electric outlet, water outlet, bench, etc. had a preestablished purpose.

Description of New Facilities

The new facility (Figure 7) is located in a basement and the most important things in its design were: (a) control of environmental parameters (humidity and temperature), (b) clean room facilities, (c) insulation from vibration and noise. Although there is a different room for each different process, all rooms are clean rooms of class 10,000 and all will have the same temperature and air humidity. In the entrance and office rooms, the personnel equip themselves to enter the clean rooms and all the glass and material is stored and precleaned in this room.

The chemical room has the facilities and space to prepare the gelatin solutions and the last cleaning of the plates to be coated. The coating booth, in this room, is a class 100 booth with control for air circulation, air temperature, and air humidity. Also in this room is a desiccator booth which has humidity and

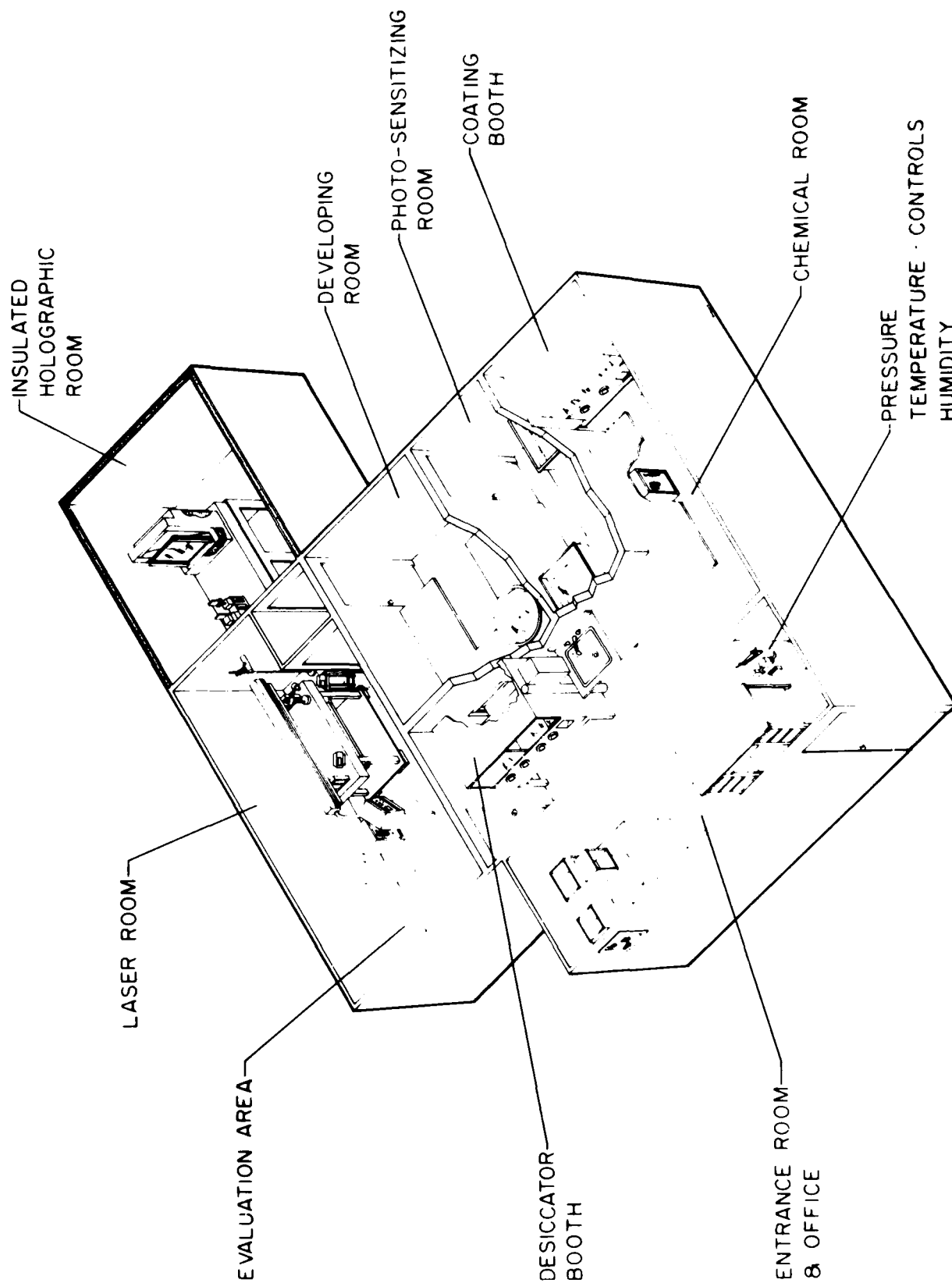


FIGURE 7. NEW HOLOGRAPHIC FACILITY

temperature controls.

The laser room is used for testing and photometric analysis (angular and wavelength response of the holographic plates).

Through a lightproof door, workers can enter the holographic room and/or the developing room and photosensitizing room.

Environmental Control. The air is recirculated, with about a 20% air intake of outside air supply which is at a constant 62°F temperature. The air circulates at a speed sufficient to produce a complete change of air every 2 minutes in all the rooms. The system includes heaters, humidifiers, and dehumidifiers. The rooms have temperature control which automatically controls the heater within $\pm 1^{\circ}\text{C}$. They have a humidistat which automatically controls the humidifier and dehumidifiers. They also have an air pressure control which automatically closes or opens the exhaust damper to produce a positive pressure inside the clean rooms (Figure 8).

The conditioned air is introduced in each room through 99.9% absolute filters in the ceiling; practically all particles larger than 0.3 micrometers (μ) are removed. This air sweeps through the rooms and returns by the grills situated close to floor level and opposite the filters. The return air is mixed in the ducts providing identical air parameters for all the rooms. The normal exhaust air is used to climatize the entrance room before going outside. The rooms also have independent emergency exhaust systems in the exposure room, developing room, and desiccator booth. These exhausts are also routinely used to avoid unhealthy concentrations of volatile chemicals. A remote control damper insulates the holographic room to avoid any air circulation during holographic exposures.

The coating booth (Figure 9) is a class 100 clean booth (no more than 100 particles larger than 0.3 μ per cubic foot). The plate to be coated is placed on a rotating table which operates at 2rpm. This booth has a germicide short ultraviolet light, a heater, and a humidifier. It has a reservoir of distilled water and two circulating fans: one for high volume and the other for a very small volume of circulation. Each of these fans is of continuous variable speed. This booth can

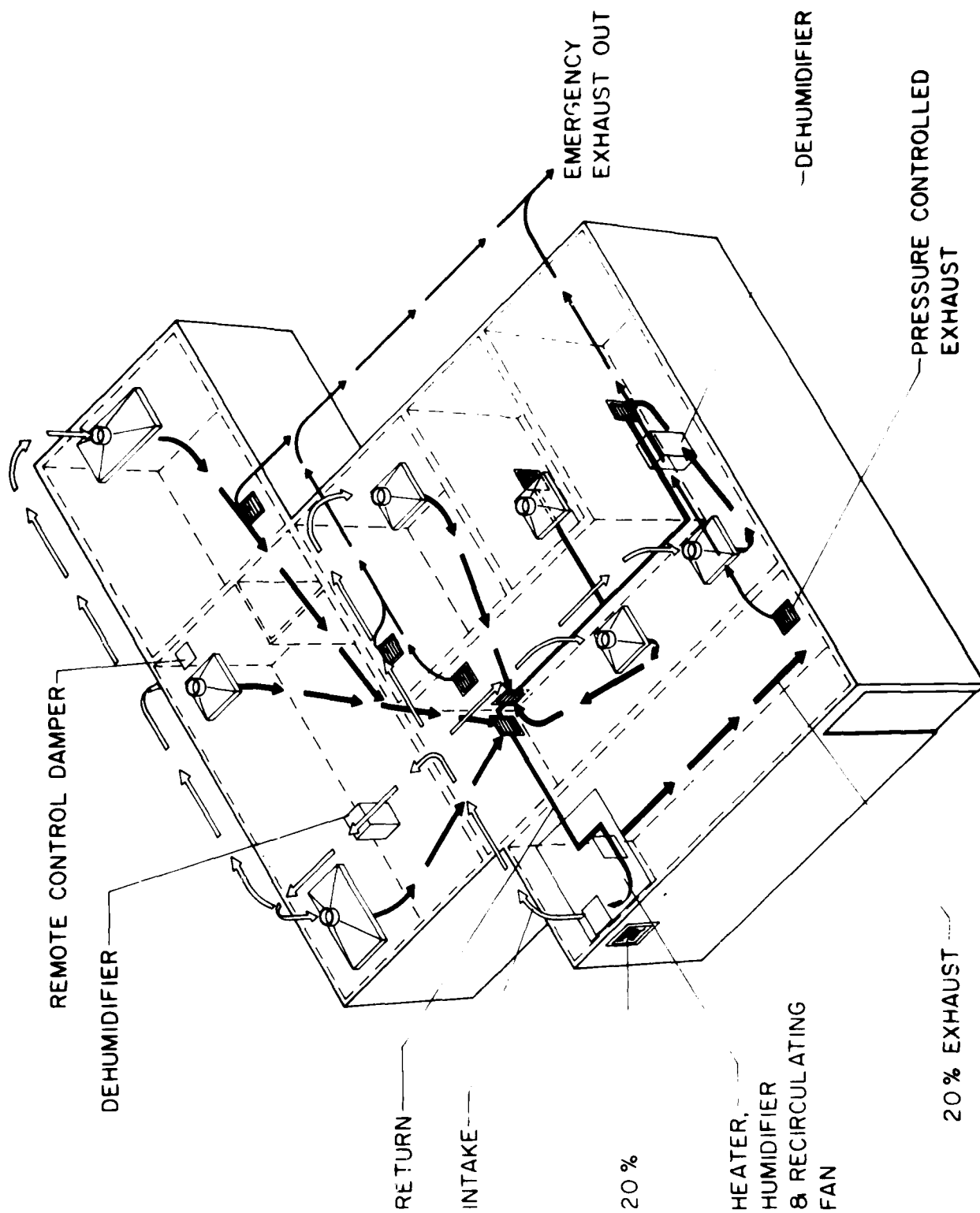


FIGURE 8. HOLOGRAPHIC FACILITIES:



FIGURE 9. COATING BOOTH

also be sealed from the air in the room. This booth was built with stainless steel and has a capacity for plates to 36" in diameter.

Once the glass plate is introduced in the booth, it is blown with dry nitrogen through a antistatic gun. The air is circulating at maximum speed sweeping the booth clean. After a while, the high volume circulation is reduced, the plate is coated, and the coating parameters are adjusted to obtain the desired flatness and hardness. Depending on the gelatin coating solution formulation, plates can be produced flat from 8 hours drying time to 48 hours, after which bacteria growth must be avoided.

Room Descriptions and Instrumentation. The laser room has an air-cushioned table which supports a 20-watt all-lines argon ion laser and a 2-watt all-lines argon laser (Figure 10). The 20-watt laser is operated with an etalon resulting in an output of about 5 watts of single mode TEM₀₀ operation in the 514.5nm line or in the 488nm line. The operation of the laser is monitored with a scanning Fabry-Perot etalon whose output is displayed on an oscilloscope. The etalon has a spectral free range of 2,000 megahertz (MHz) and the bandwidth of the laser line displayed is around 50MHz. The minimum separation of the transverse modes for the 20 watt laser is 70MHz. These lasers are water cooled and an expansion tank is used to damp variations in water pressure.

Due to the large noise and heat produced by the power supply of this large laser, the laser was housed in a room that was separate but adjacent to the room containing the holographic table. The laser beams are sent through a 0.5" tubular hole in the partition wall. In this wall, there is also a conical visual port to observe the holographic table and a port-lens system to display interference fringes from the vibration monitoring interferometer.

The holographic room is a room insulated with an extra wall of noise insulating material and a double, nylon cord suspended ceiling. The holographic tabletop, a granite slab 48" x 70" x 10", is supported by air tubes. The mirror, originally vertically mounted on the table, is an aluminized glass mirror with a 48" radius of curvature and 38" x 40" aperture (Figure 11). The mirror is damped at the supporting base and at its back with small plastic bags filled with sand (about 200 kilograms of sand).

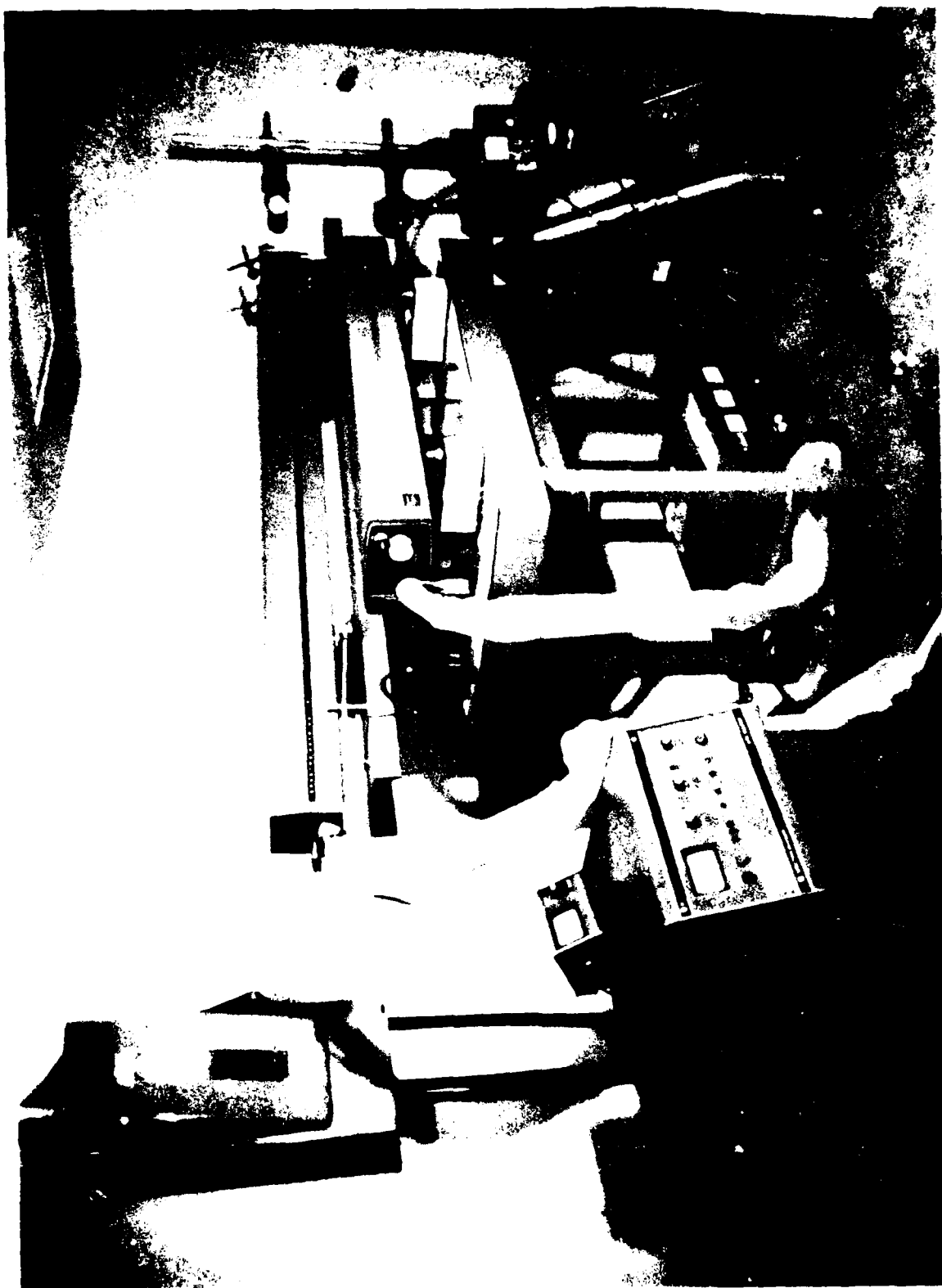


FIGURE 10. APPLICATORS AND LAYER ROOM

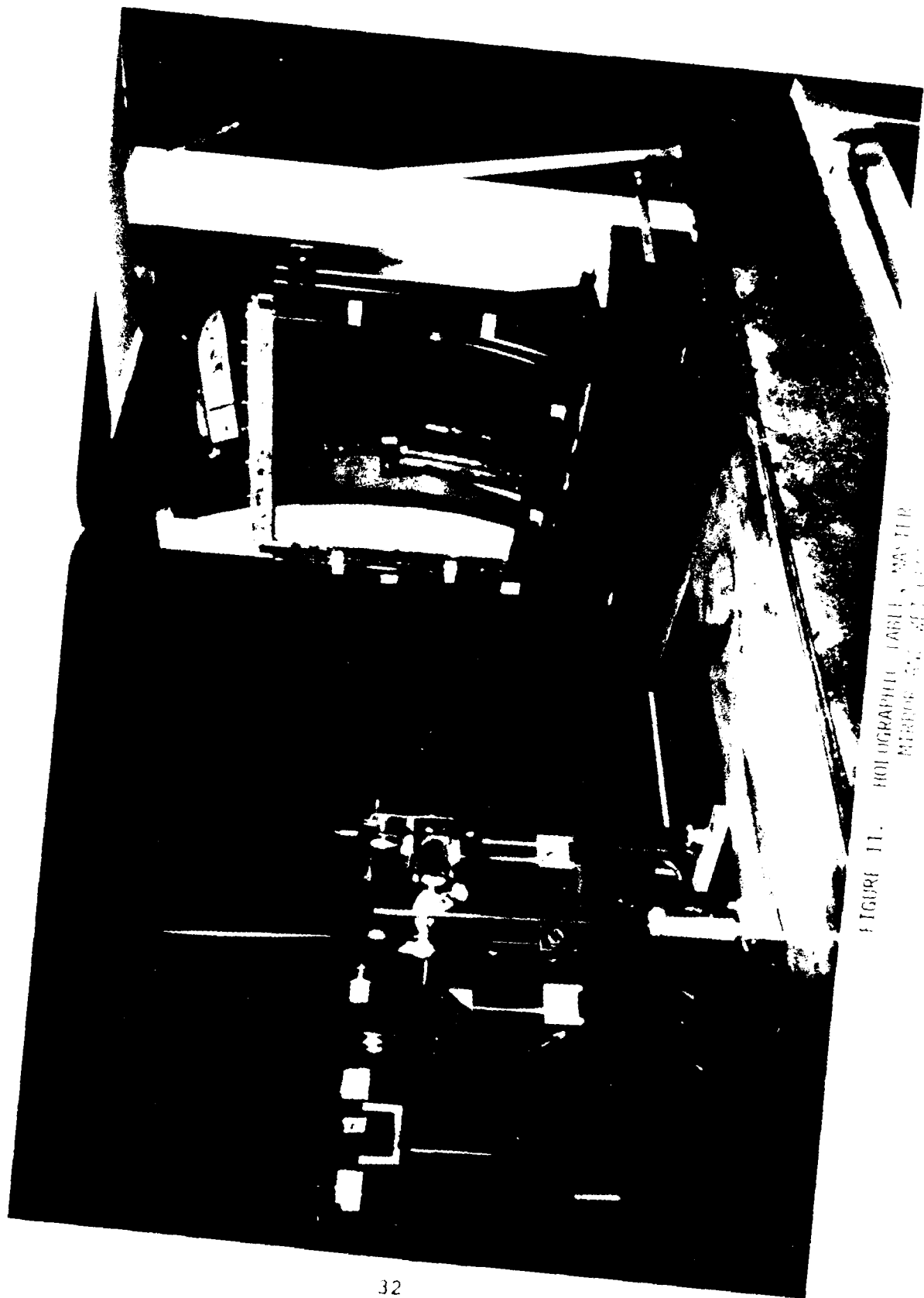


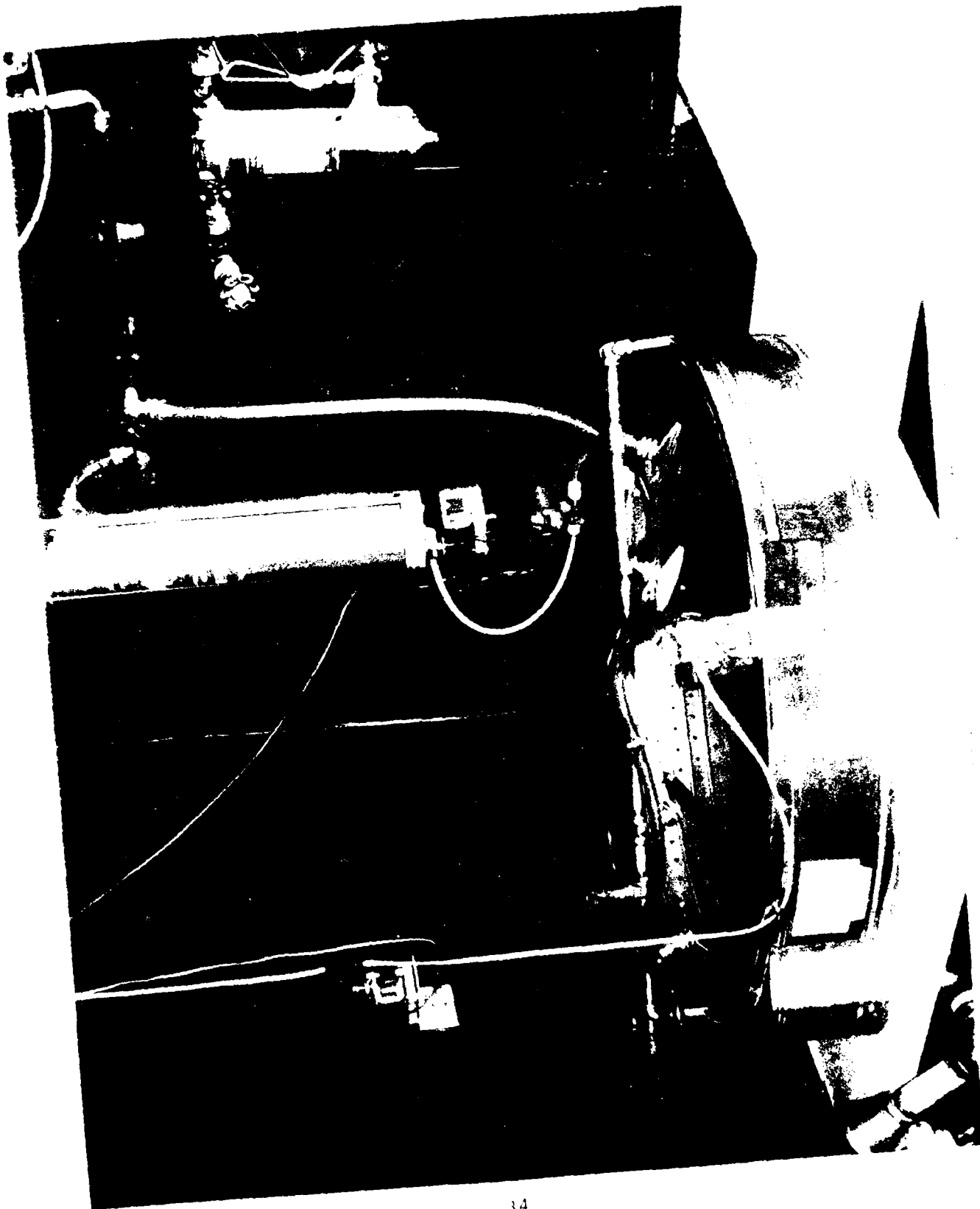
FIGURE 11. HOLOGRAPHIC TABLE MASTER
REPRODUCED FROM REF. 11

The wet cell, which was (initially) utilized to eliminate unwanted reflections, has glass coated with high efficiency AR glass and a thickness of $3/8$ ". This wet cell is useful for plates with a maximum size of 24" x 21.5" (Figure 11).

A 3 milliwatt (mW) helium-neon laser is used to monitor vibration in the wet cell or in the mirror after the photo-sensitized plate is in place, before, and during the exposure.

The developing room has a supply of demineralized water whose temperature is controlled to $\pm 1/2^\circ\text{C}$. The washing tank, which can be used for plates to 36" in diameter, has multiple shower heads, control of water level, exhaust through the bottom and a rotating inner tank driven by a small motor (Figure 12). This room communicates through a trap window to the desiccator booth where the plates will be dried after development.

Figure 13 shows the holographic beamsplitter mirror analyzer. A monochromator with a resolution of 10nm illuminates the holographic plate through a collimating lens. The light reflected at the mirror is focused at the window of a photocell. A system of gears automatically displaces the photocell for each angle of incidence. This instrument provides a fast analysis of the wavelength and angular response of the holograms.



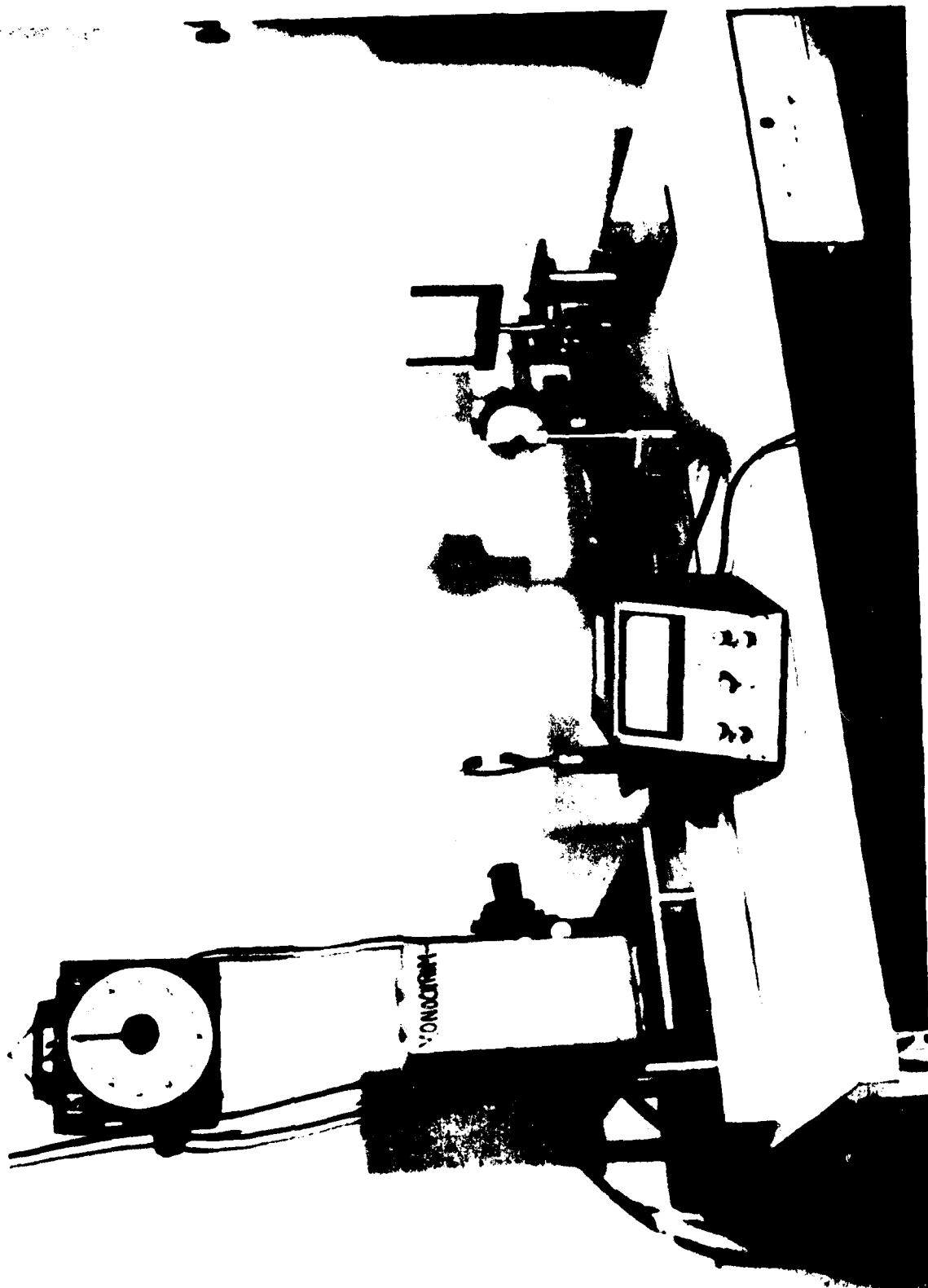


FIGURE 13.
HOLOGRAPHIC SPHERICAL MIRROR ANALYZER

SECTION IV
HOLOGRAPHIC SPHERICAL MIRROR
ADDITIONAL DEVELOPMENT

Introduction

In order to repeatedly reproduce holographic spherical mirrors of acceptable quality, considerable research into several factors was required. This section describes the development efforts: (a) to improve gelatin film flatness, (b) to improve thickness uniformity of the gelatin film, (c) to improve control of hardness, (d) to investigate holographic recording with a wet cell, (e) to investigate spectral response characteristics of the holographic spherical mirrors, and (f) to investigate diffraction efficiency characteristics of the holographic spherical mirrors.

Improved Flatness of Gelatin Film

Causes for Lack of Flatness. The flatness of a gelatin film is affected by rapid drying, which produces an orange-peel effect; excessive airborne dust settling on gelatin, which causes craters and surface defects; non-uniform drying times for different areas of the gelatin; and exceedingly long drying times encourages bacteria growth in the gelatin. The growth of bacteria is extremely detrimental to the flatness and usefulness of gelatin.

Proposed Solutions to Flatness Problems. To control the drying time of the gelatin film, the gels were produced in a class 100 clean booth with environmental control over temperature, air movement, and relative humidity. To control uniformity of drying time for the entire film, the coating substrate was rotated. This was to insure uniform relative humidity over all areas of the film. To remove dust from the coating environment, all coating was done in a class 100 clean booth.

Experiments to Improve Flatness of Gelatin Film.

To remove orange-peel effects and not allow bacteria growth, the drying period of the gelatin film was varied by changing the environment in the class 100 coating booth. The booth was allowed to operate at two temperatures (room temperature 21°C and high temperature 27°C) and at three relative humidities (low 40%, 90%, and high humidities near 100%). All these parameters were tested with the substrate rotating (Table 2).

Results from Experiments. Coating in low humidity with 21°C and 27°C temperature and in high humidity (100%RH and 90%RH) with a 27°C temperature caused the film to dry too fast (30 hours) and resulted in an orange-peel effect. Coating in high humidity (100%) and low temperature (21°C) caused the film to dry too slowly, greater than 48 hours, causing bacteria growth. However, when coating in 90% relative humidity at room temperature 21°C, the gelatin dried in 38 to 40 hours and produced a film without orange peel or bacteria growth.

By coating in a class 100 dust-free environment on a rotating table, there was no dust to settle on the gelatin and cause craters or surface defects, etc. Also all areas of the gelatin film dried at the same time, yielding a uniformly flat film.

Methods of Analysis of Film Flatness. The dried gelatin film was viewed by shadow casting in laser light from a pinhole on a white screen. As a result of shadow casting, orange peel effects, dust, and any other nonuniformity from drying were magnified so they could be easily seen. The dried film was also viewed directly at grazing angles. By viewing at these angles, any dust, gross orange peel effects, and gross nonuniformities could be seen.

Final Results of Flatness Improvement Techniques. Use of the class 100 booth and rotating table led to the coating of high-quality, flat gelatin films.

A 21.5" x 24" plate was coated with gelatin solution and rotated levelly at 2 cycles/minute in an atmosphere of 90% relative humidity and temperature of 21°C with small air movement caused by a small fan located lower than the substrate. The small fan allowed some air movement but no air currents strong enough to cause non-uniformities in drying. These parameters yielded a flat gelatin in 38 to 40 hours drying period.

Improved Thickness Uniformity of Gelatin Film

Table 2. COATING PARAMETERS

1. Low RH, 27°C
2. " " , 21°C
3. 90% RH, 27°C
4. " " , 21°C
5. 100% RH, 27°C
6. " " , 21°C

Lack of film uniformity in thickness was related to two principal causes: (a) improper leveling, a necessity in gravity coating caused thickness variations in the film across the plate; and (b) nonuniform drying caused thickness variations in the film.

Proposed Solutions to Thickness Variation Problem.

To insure proper leveling of the substrate, it should be coated on a substrate resting on a machined leveling table. To insure uniform drying, this mechanical leveling table should be rotated in the proper environment. The rotation will also average out any small leveling error.

Experiments to Improve Thickness Uniformity. The substrate was leveled to within .001" per foot and coated. This film was photosensitized and exposed. The substrate was rotated at a speed of 2 cycles/minute and coated. This film was photosensitized and exposed.

Results from Experiments. The leveled substrate was checked when gelatin was dry and found to still be level. The plates exposed showed no nonuniformities in wavelength response or diffraction efficiency from thickness variations. The film also showed no variations in thickness due to nonuniform drying as checked by shadow casting in laser light and by examination of exposed plate's uniform wavelength response and diffraction efficiency.

Method of Analysis of Uniform Flatness. The plates were exposed and examined for uniform spectral response and diffraction efficiency. Viewing of plates was accomplished by shadow casting laser light to show difference in uniformity.

Final Results of Uniform Thickness Improvements. A uniformly thick gelatin film was produced using leveling techniques and a rotating table to average out any small leveling errors and to insure uniform drying. These techniques will form a uniformly thick gelatin. The resulting thickness depends on the gel concentration poured on the substrate.

Improved Hardness Parameters

Gelatin film suitable for holographic recording must have a specific hardness for a given application. Producing gelatin films with a specific hardness repeatedly is also a concern. Repeatability was found to be affected by variation in environmental conditions and the use of gels

of varying ages. Irregularities in hardness have been found to be caused by nonuniform drying of the gelatin.

Proposed Solutions to Hardness Variations. The gelatin films should be produced in constant environmental conditions so each plate will have the same characteristic hardness. The coatings should be dried uniformly by drying them in the class 100 clean booth with environmental controls. The gelatin films should be used before their age becomes a factor in hardness or gelatin films of the same age should be used consistently.

Experiments to Improve Repeatability and Uniformity of Hardness and Yield Gelatin Films of Different Hardness. Gelatin films were coated in consistently the same environment to yield similarly hardened plates, that is, in the class 100 booth with environmental controls. This insures a uniform drying period and, therefore, uniform hardness. Drying the gelatin slowly or quickly was done to yield different hardnesses in the gelatin films.

Procedure for Experimental Analysis. The plates were compared, after being similarly exposed and developed by measuring their diffraction efficiency and wavelength response. Their uniformity across the plate in diffraction efficiency and wavelength response was also visually evaluated.

Experimental Results. Those gelatins coated in the same environment had consistently the same hardness characteristics. They also showed uniform diffraction efficiency and wavelength response across the plate. Rapidly dried gelatin films were softer than slowly-dried gelatin films.

Final Results. Environmental controls which allowed consistent drying periods and uniform drying yielded a uniform and desired hardness.

Holographic Recording with a Wet Cell

In order to improve the quality of the holographic spherical beamsplitter mirrors, the use of wet cells for recording was explored. Several designs were developed, constructed, and evaluated. This work showed the desirability of wet cells in recording.

Demonstrated Recording Improvement with Initial Oil Tank. To explore the viability of wet cell recording, an

oil tank (Figure 14) was constructed. It was made of aluminum with an AR coated window on the slanted side to avoid internal reflections. Immersed in the oil of the tank was a 48" radius of curvature, 4.5" x 5.5" mirror and a 4" x 5" plate. The mirror was located on the far wall of the cell with the plate positioned 1" in front of the mirror.

Compared to recordings made without the tank, recordings using the tank were cleaner, due to the removal of surface fringes caused by plate surface reflection recording and removal of secondary recordings due to multiple reflections between mirror and plate.

4" x 5" Wet Cell as a Prototype for Large 21.5" x 24" Wet Cell. The 4" x 5" wet cell consisted of a metal frame with two 4.5" x 5.5" AR glasses cemented to it, forming an open topped cell. The top of the cell could be screwed down and had a bar with screws to press on the inserted 4" x 5" plate. The cement for holding the AR glasses and sealing the cell had to be chosen carefully because of the index matching liquids to be used. Since most of the organic liquids with a refractive index very close to 1.52 were solvents (benzene, xylene, etc.), a solvent resisting (3M 801) sealant was used to cement the AR glasses in place.

The index matching liquid had to have a refractive index of 1.52 and to be colorless. Many liquids were tested: tetrachlorethylene, benzene, xylene, anisole, methyl benzoate, chlorobenzene, toluene, and mineral oil. All except the mineral oil produce harmful vapors. The mineral oil, though, is too viscous and traps air bubbles, which cause noise if they are in the recording path. Tetrachlorethylene was chosen because it produced the least amount of fumes and the least harmful fumes.

During exposure, the 4" x 5" plates were held in place and stabilized by the bar in the cell top which was screwed down on the plate. The plates exposed showed no surface fringes from surface reflections being recorded and no secondary reflection recordings due to recording of multiple reflections between wet cell and mirror. This proved that AR coated glass reduced the reflections of surfaces to an acceptable level and that the index match of the liquid was consequently correct.

21.5" x 24" Vertical Wet Cell. This large cell (Figure 15) was a scale up of the 4" x 5" wet cell. With this cell though, black bands resulted. Black bands are interference band recordings (similar to interference rings)

SPHERICAL MIRROR

HOLOGRAM PLATE

ANTI-REFLECTION COATED
WINDOW NOT NORMAL TO THE
INCIDENT LIGHT

OIL

LASER LIGHT

FIG. 14 OIL TANK GEOMETRY

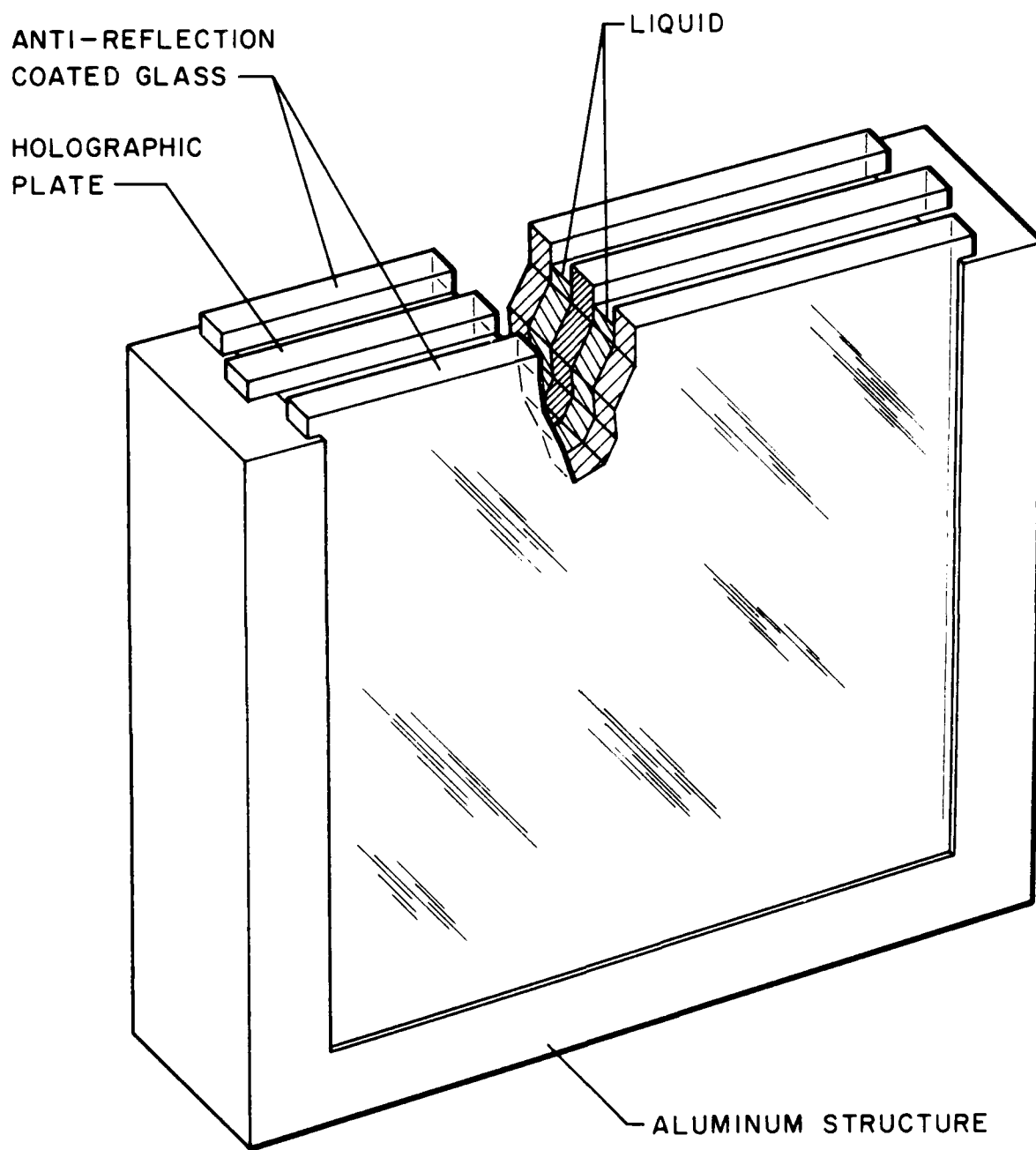


FIG. 15 VERTICAL CELL (SKETCH)

caused by mechanical, or laser, instability during the recording of the hologram. These bands are superimposed and will mask the reflection from the holographic mirror in these areas. They will be analyzed in Section V. It was felt first that the cause might be the hydrostatic force of the column of tetrachlorethylene bending the glasses out to cause a continuous swelling of the cell. One of the AR glasses broke under this hydrostatic pressure due to the clamping techniques of the glass. The thickness of the glasses was increased from 1/8" to 1/4" and additional clamping was added especially at the unsupported top of the cell. Also for safety consideration, adaptations were made so the index matching liquid could be added after the plate was loaded in the cell and the AR glasses were clamped for support.

This did not solve the black-band phenomenon, so improvements were made in the plate holding techniques. It was felt that the plate, because it was standing under its own weight, might be sagging continuously. Many techniques were tried to support the plate uniformly, e.g., 1/16" rods covered with Teflon tubing supported the glass on its sides, and new screw clamping from the sides supported the top. These techniques reduced the number of black bands produced but did not remove them.

17" Horizontal Lens Mirror Wet Cell. The hologram construction geometry was varied from vertical to horizontal to change the plate support parameters and remove the hydrostatic forces. The 17" horizontal lens-mirror consisted of a 17" diameter plane-convex lens with the concave surface coated with aluminum. It was supported in plaster of Paris and floated on air (Figure 16).

The plate had to be held stable. To stop the plate from continuously pushing liquid out from under it and so continuously moving, spacers were placed between the lens mirror and the plate. These spacers stopped the liquid from being pushed out continuously, but due to gravity, the plates sagged under its own weight. This sagging produced black bands similar to those seen in the 21.5" x 24" wet-cell produced hologram. This would support the theory that the plate in the large cell needed better support through clamping.

To keep the plate from continuously pushing out

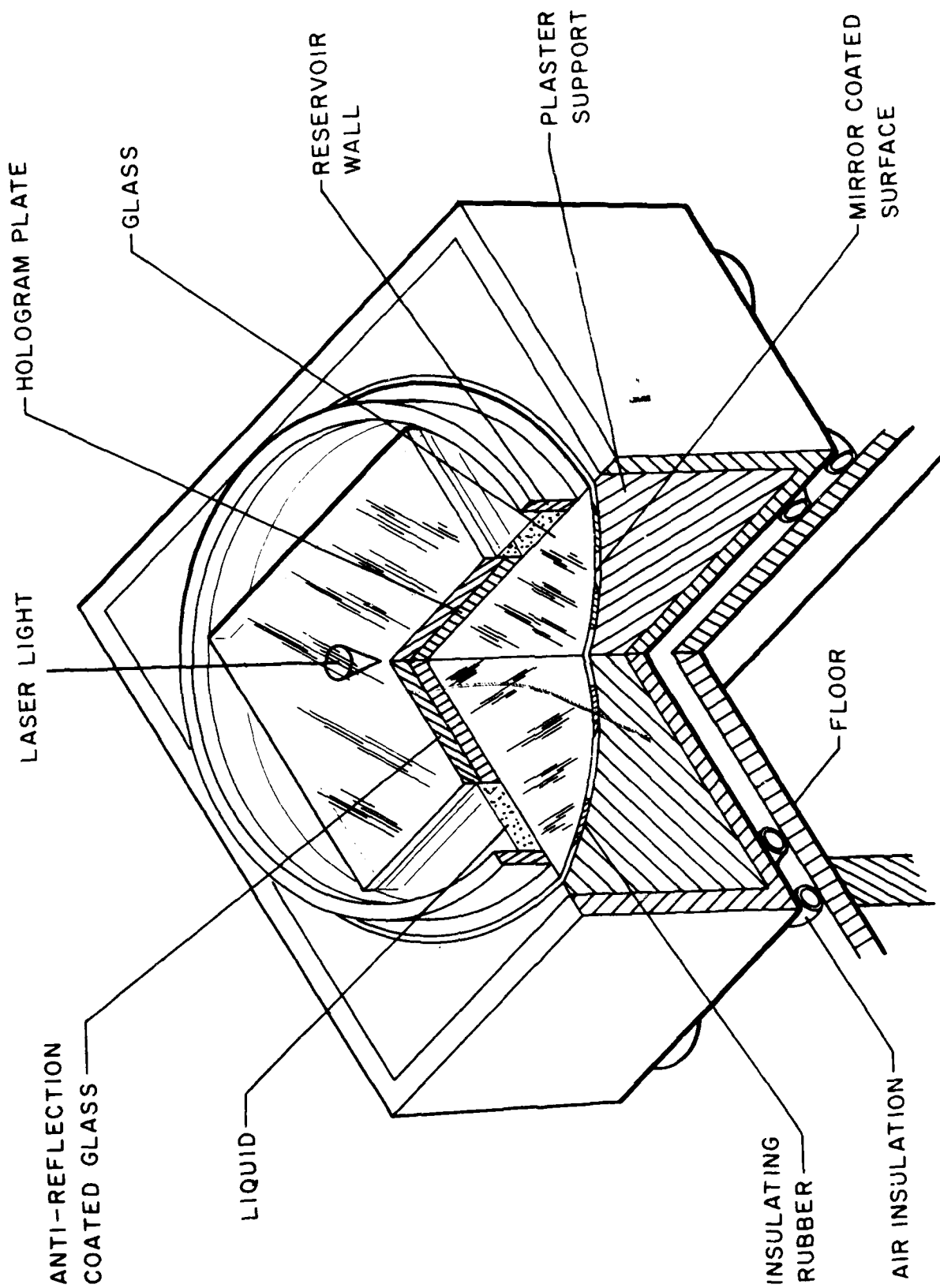


FIGURE 16. LENS MIRROR WET CELL

liquid, a reservoir was built around the lens mirror. This reservoir (with clamps for the plate) solved the continuous liquid movement problem by immersing the plate in the liquid so it would eventually reach an equilibrium state.

The lens mirror with a reservoir and plate clamping yielded a stable plate and therefore a plate with no black bands, signifying a good recording. The hologram had a smaller secondary reflection recorded in it if an AR glass was not placed over the holographic plate. The cell to mirror path is solid glass. Consequently, only one AR glass was required to form the cell.

17" Horizontal Wet Cell. This cell was composed of a 17" spherical mirror with a 0.5" thick base plate over it. The base plate had a reservoir and AR glass cemented to it. This base plate was supported but not in contact with the mirror. This prototype was tested because the large horizontal wet cell for the final holograms would be a scaled version of this system.

It was found that having the base plate in contact with the mirror yielded an unstable system but if the base plate was supported separately from the mirror but on the same structure, the system was as stable as the lens mirror system.

The horizontal wet cell yielded a good holographic recording, but now the secondary reflection was stronger due to reflection off both surfaces of the cell and was recorded in the hologram. Nevertheless, one of the holograms produced was placed in the Pancake Window configuration and the second reflection recording could not be noticed.

Horizontal Wet Cell. The large horizontal wet cell was a scaled version of the 17" diameter wet cell. It consisted of the 40" x 38" Master mirror supported in a box of sand, a 1" thick glass plate with an AR glass and reservoir cemented to it, and an air supported base on which the glass plate and box of sand with mirror were independently supported, (Figure 17). With this system, good recordings were achieved with no black bands.

Vertical Wet Cell Improvements. Through the use of the horizontal systems, it became apparent that the failure of the first 21.5"x 24" vertical wet cell was due to the plate being supported incorrectly. A new cell was designed where the plate and AR glasses would be equally

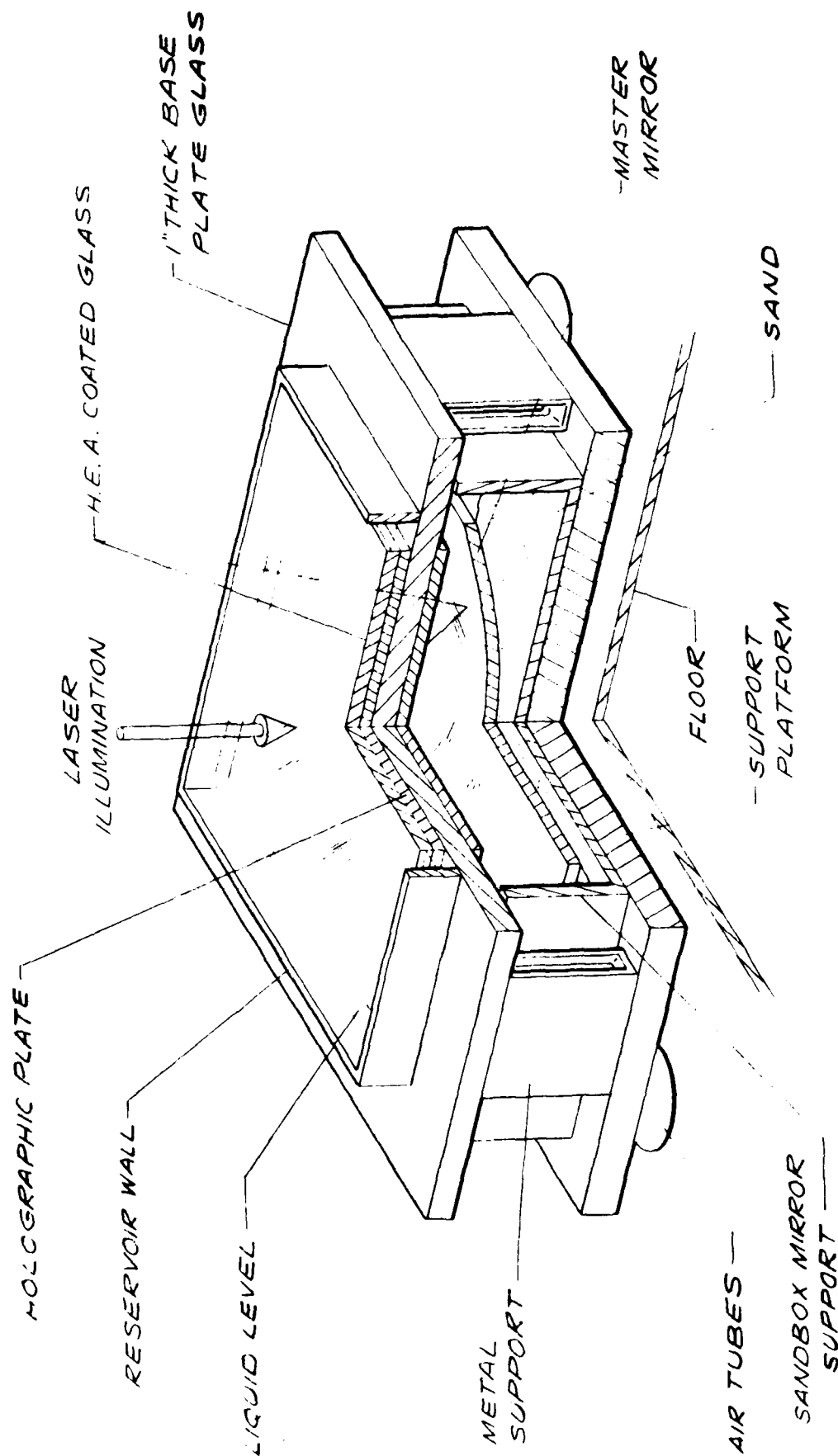


FIG. 17 HORIZONTAL WET CELL

supported on all four sides. This design was expected to remove any sag from the glass and any strain from nonuniform support, (Figure 18). With these corrections, the vertical wet cell may work. However, no further work was done on the vertical cell because of the great success of the horizontal system.

Final Results of Wet Cell Use. Use of the horizontal wet cell provided nearly 100% repeatability in production of good quality holograms. Due to surface reflections, no holographic plane beamsplitters were recorded in the hologram, and the secondary reflections being recorded were reduced to the point where they had no effect when the holographic mirror was used in the Pancake Window configuration.

Improvement Required as a Consequence of the Evaluation of the 17" HPW

The evaluation of the 17" HPW shows a need for improvement in reference to (a) new ghost images, (b) contrast and resolution, (c) cosmetic appearance.

It was found that the new ghost images (called new ghosts to differentiate them from the normal ghosts in the Pancake Window display) were caused by multiple hologram recording due to secondary reflections in the HBSM construction component surfaces. The use of a wet cell removed or reduced, to insignificance, all the new ghosts in the HPW.

The contrast and resolution, principally on the HPW axis, deteriorate as a consequence of the relatively narrow spectral response of the HBSM together with a diffraction efficiency higher than 50%. It was explained in Section II of this report that a HBSM reflection higher than 50% could cause a HPW double peak spectral response which would produce a doubling of the images reflected by the HBSM and consequently a loss in contrast and in resolution. This double peak spectral response is not of concern if the HPW is to be illuminated by a very narrow spectral source, as the P-44 phosphor, since the doubling of the images, or its effect, could not be observable. On the other hand, the use of a much wider spectral source as the P-31 phosphor will require a HBSM with a diffraction efficiency (reflection) smaller than 50% to avoid the loss of contrast and resolution due to the doubling of the reflected images.

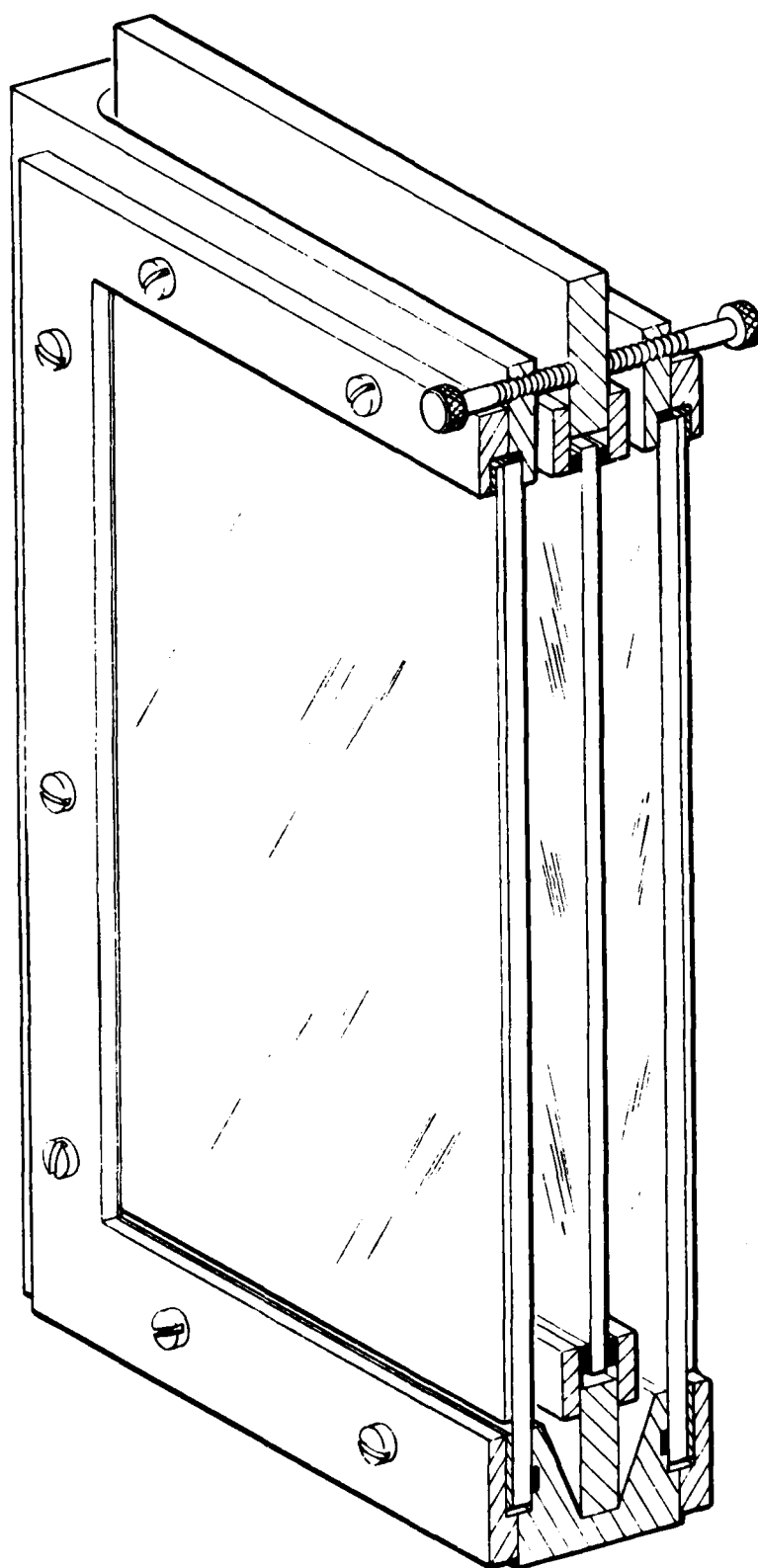


FIG. 18 IMPROVED VERTICAL WET CELL

The poor cosmetic appearance was related to the physical characteristics of the gelatin film plus an undesired recording of a plano (not volume) hologram due to surface reflections in the HSBM substrate. The improvement of the physical characteristics of the film as hardness, uniformity, flatness, etc., has been described above in this section. The undesired recording of the hologram is avoided with the use of the wet cell.

SECTION V

PROCEDURE AND APPARATUS FOR THE PRODUCTION OF THE HOLOGRAPHIC SPHERICAL BEAMSPLITTER MIRROR (HSBM)

Description of Geometry

The hologram to be used as a HSBM requires the recording of the interference pattern of two oppositely directed coincident spherical wavefronts, one divergent, the other convergent, from and to the same point, (Figure 4). This interference pattern at a particular wavelength must be recorded in the volume of an emulsion of correct thickness and sensitivity to the illuminating wavelength.

An argon ion 20-watt laser was operated at 514.5nm single frequency and TEM₀₀ mode.

The laser beam passed through the laser room's wall and was reflected 90° down toward an expander lens, microscope objective and spatial filter by means of a high reflectance aluminized mirror at 45° to the beam. The beam passed through an AR coated negative lens $f = 7.5\text{cm}$ to expand the beam. The expanded beam was incident on a 40X, .65 N.A. microscope objective (M.O.). The beam was expanded enough to allow only the uniform part of the beam to enter the M.O. The light passing through the M.O. was focused at a 20um spatial filter. The spatial filter approximated a point source and was positioned at the radius of curvature (R of C) of the master mirror.

The master mirror was 38" x 40" x 1" in size, with an R of C of 48" and a sagitta of 7". It was positioned on-axis, 48" from the spatial filter. The front surface of the positive side of the mirror was coated with aluminum. The mirror was supported in a box of sand to damp out any vibrations. Above the mirror was placed the base plate of the horizontal wet cell, a 50" square, 1" thick, strain-free glass. On one side was cemented an AR glass and on the other a reservoir in which the emulsion and top AR glass were laid. This baseplate is supported by blocks, above the mirror, on a 48" x 48" air floated base. The sand box with the master mirror is also on this air-cushioned base.

The photosensitive emulsion and AR glass must be in optical contact using an index matching liquid: tetrachloroethylene. These must be laid down without any air bubbles being trapped. This was done by forming a puddle of tetrachloroethylene along one wall of the cell and laying the emulsion on the liquid as it is squeezed out and spread over the cell. The plate is left to settle for at least one hour before exposure.

When the plate is exposed, light travels through the emulsion and is reflected back on itself by the master mirror. This reflected convergent spherical wavefront interferes with the divergent spherical wavefront from the spatial filter. This interference pattern is recorded in the volume of the gelatin.

Wet Cell Geometries and Performance

Purpose of the Wet Cell. Light moving from one medium to another having a different index of refraction will be reflected at the interface of the two differing indices. When a plate of gelatin emulsion and glass substrate is exposed in air, the spherical divergent and convergent constructing wavefronts are thus reflected off the interfaces. These reflections generate new wavefronts which can be recorded by the emulsion. The particular reflections most bothersome are the multiple reflections between the plate and mirror and the reflections off the plate itself. The use of a wet cell with AR coated windows will remove or reduce these reflections so they will not be recorded, or at least the recording will be minimized.

Secondary Reflections

Description of the Secondary Reflections. These reflections are produced (a) between the wet cell AR glass surfaces and (b) between these surfaces and the master mirror ("second reflections").

The strength of these reflection recordings in the emulsion is dependent on the beam ratio of the incident light from the laser and the light from the secondary reflections. The light intensity of the second reflection depends on the position of the photosensitive plate. If the plate position is coincident with the secondary focus (from the second reflection) the recording is strong due to the concentration of the weak reflection from the large

AR glass area in one point. The recording of the second reflection becomes progressively weaker as the plate is positioned further away from this secondary focus, either toward or away from the master mirror.

Effects of the Secondary Reflections. If the recording is made at the secondary focus position, then a flair would be recorded in the center of the hologram. If the recording is made above or below the secondary focus, an ellipsoid or hyperboloid secondary mirror will be recorded. At some finite distance from the secondary focus the beam ratio will fall to a point where no second reflection will be recorded. If these plates are exposed in air, the flair caused by the exposure at the coincident point will now cause a "bullet hole" to be recorded and instead of one or two ellipsoids or hyperboloids being recorded, four or five will be recorded. These phenomena are due to the multiple reflection off the plane glass surfaces, which now have enough intensity to be recorded. If the "bullet hole" is recorded, it will leave a void in the hologram. If the recording of the second reflections is close to the secondary focus, then the recording will be strong, causing the area of recording to have a different wavelength response than the rest of the hologram and a lower D.E. This is true if the plate is from 0" to 3" or 4" away from the secondary focus. If the second reflection is recorded with the plate 5" or more away from the secondary focus, there will be no appreciable effects from the recording.

Stability Problems (Black Band Effects)

The holograms produced using the first built 21.5" x 24" vertical wet cell exhibited what was called the black band effect. The black bands are areas in the HBSM where light is not being diffracted and usually they had a format similar to (although much wider than) the interference fringes in an interferogram.

The black band problems were due to four possible causes: (a) The laser operating with a mode instability, (b) The laser beam heating the optics, (c) Mechanical instability in the optics defining the interferometric path: the plate holder and master mirror, and (d) An inherent problem due to plate position, air space, or light polarization changes.

These causes were investigated and by an illumination process it was determined that the black bands were produced

by an unstably operating laser and by an unstable holographic plate which was improperly supported inside the vertical wet cell. The unstable laser tube was replaced and the support of the holographic plate was improved using a different wet cell geometry, specifically the horizontal wet cell.

Tests and Experiments to Find the Cause of the Black Band Effect. The laser mode stability was checked with monitoring interferometers and a Fabry-Perot etalon and compared with another laser as to ability to produce good recordings. The Fabry-Perot etalon was checked for its ability to resolve laser modes. To insure stability the laser was insulated from air currents and water pressure surges of the cooling system.

The possibility of laser beam heating of optics causing the black band effect was checked by keeping the optics constantly illuminated by the laser beam by placing the shutter after the spatial filter and by using different shutters before the optics and checking possible heating of the wet cell by use of half area exposures at different times.

Mechanical instability in the holder (wet cell) and master mirror for vertical and horizontal positions was checked by:

1. Making comparison of the interferometric stability of each individual component. This was to find one problem element.
2. Insulating each component of the system from the other to isolate the problem area.
3. Removing air currents which might be initiating vibrations in the components.
4. Insulating each component from mechanical vibrations by deadening in sand or spacing with high frequency absorbing rubber.
5. Testing the body stability of the wet cell by interferometric methods.
6. Checking plate stability in the wet cell by interferometric methods.
7. Checking plate stability in liquids by testing different liquids and half-filled cell.

To check for some inherent problem in the system, the

plate position was changed to produce different R of C holograms, and empty cell (no liquid) exposures were made to check that the liquid had no optical rotation effects and holograms were produced with different wavefronts, e.g. to produce parabolas. Also exposures were made with light of different wavelengths.

Results of the Search for the Cause of the Black Bands.

The results of the experiments investigating the effect of the laser beam heating of optics showed this not to be the cause of the black bands. The exposures made with the shutter after the spatial filter and the use of different shutters before any of the optics did not eliminate the black band formation. The half exposures (those exposures made with each half of the plate exposed at different times) showed the black bands to not be static, suggesting the problem was not due to heating of the optics.

From tests run to check laser mode stability, it was found that stopping all air currents removed fast vibrations seen in the oscilloscope readout from the Fabry-Perot etalon and in the interferometers setup. The addition of an expansion tank to the laser cooling system removed some noise observable only in the oscilloscope readout from the etalon. The etalon was examined and found could resolve the modes of the laser so that a single peak oscilloscope readout meant the laser was operating single frequency. Holographic recordings were made with the 20-watt argon laser and with a 2-watt argon laser. The holographic plate was supported without the use of a wet cell (with the plate holder and 17" master mirror used in producing the 17"HPW). Holograms made with the 20-watt laser showed black bands but these were not present when the holograms were made with the 2-watt laser. Consequently, a new laser tube for the 20-watt argon laser was installed and the absence of black band recording with this laser was verified. Nevertheless the black band effect was again observed when the lasers were used with the vertical wet cell and the large 40" x 38" vertically held master mirror. These results showed that the instability of the old laser was not the only cause of the black bands.

Interferometric testing showed that the vertical wet cell and/or the master mirror in the vertical system were unstable.

The original design of the vertical system had the wet cell and the master mirror locked together. It was believed that in this configuration, the instability might be

transferred from one element to the entire system. To find a single cause each element was separated from the other and examined interferometrically. It was found here that each element was again periodically stable but none were stable over time. Also over the long viewing periods small fringe movement in the monitoring interference pattern was difficult to discern.

When air currents were removed by shutting down the laboratory air system, some vibrations (the fast vibrations) were removed and the system proved more stable, but the slow or low frequency vibrations continued.

To remove this low frequency vibration the wet cell and master mirror were insulated from mechanical vibrations by deadening with sand or high frequency absorbing rubber. This greatly improved the stability of the master mirror.

The wet cell body was checked for stability and found to be quite stable. This was proved by a recording free of black bands produced by an air exposure with the plate held in a wooden frame clamped to the wet cell body.

The plate in the cell was suspect. To check the stability of the plate, a 21.5" x 24" glass plate with a beam-splitter cemented to it was introduced in the cell and checked interferometrically for stability. The plate showed some unpredictable stability. The same results were obtained using a 21.5" x 24" beamsplitter of the same thickness instead of the holographic plate.

To further isolate the problem of instability of the plate in the cell several tests were done with index matching liquids. The stability was not improved with the use of mineral oil, a heavier liquid to help damp out vibrations. The wet cell was half filled and each half was exposed at a different time. The results showed the situation non-static. Both halves had different black bands. The movement was continuous and not related to submersion in the liquid.

Although it was possible to improve the stability of the vertical wet cell body and the vertically held master mirror with better support and dampening, all the attempts failed to make the holographic plate inside the vertical wet cell stable. Consequently, and as has been described in Section IV, experiments for holographic plate stability were made using different wet cell geometries.

Experiments showed the plate holder (wet cell) and

master mirror in the horizontal wet cell system were stable. The horizontal wet cell system was checked by placing a BS on the base plate and viewing the interference pattern. The pattern was consistently stable, and when disturbed, the system damped out in approximately 1 minute. The system remained stable with and without air currents present.

A check of plate stability in the liquid showed that the plate, after reaching equilibrium in the reservoir (approximately 30 mins.), was very stable for even the long exposure period of 15 minutes.

Characteristics of the Horizontal Wet Cell

The horizontal wet cell consists of a liquid reservoir 22.5" x 25" built over a 1" thick, 52" square glass base plate. The holographic plate is immersed in the reservoir and is covered with an AR glass to avoid liquid-air surface reflections. Another AR glass is cemented at the other side of the glass base plate to minimize glass-air surface reflections. This horizontal wet cell is held over but independent of the master mirror using two 1.5" x 4" iron channels. The iron channels are supported by 4 metal blocks which are supported on the same air-floated base as the master mirror (Figure 17).

Tetrachlorethylene with (an index of refraction) $n = 1.505$ was used as an index matching liquid because it did not attack the reservoir's cement. The liquid matched well with other components.

The walls of the reservoir were made of 1" high steel strips cemented in place with a epoxy in a rectangle 22.5" x 25". It included 5 cemented pods outside the reservoir. Each pod had an arm to swing over the cell, each arm with a screw to hold the emulsion and AR glass down and in place. This reservoir worked well. In fact, after the horizontal wet cell was developed it was the most reliable part of the hologram production process.

Comparison of the Horizontal Wet Cell with Alternate Systems. When it was found that the photosensitive plate was held incorrectly, a new improved vertical wet cell was designed and built. This cell was designed to hold the plate stably and uniformly and would be sealed on all four sides (no open top).

The lens mirror cell is a plano-convex lens with the

convex side aluminized. The cell body would be more stable since the interferometric path would be in solid glass except for the liquid under the plate. The second reflections would be less intense for the lens mirror (LM) system because the system has only one AR glass reflection, not two as with the horizontal wet cell system (HWC). The LM system's thick lens would also have less curvature, for equal R of C, than for the HWC system. The only drawback would be the lack of ability for variations in construction of the holograms with different radius of curvature.

Polarization techniques could eliminate the secondary reflections. The use of quarter wave plates, polarizers and oppositely directed beams (no back mirror), could eliminate the need for a wet cell. The reason consideration was given to this system was that the plate could be held in air. The stability needed is easier to obtain without the liquid interface. The major drawbacks of this system are (a) the losses of light from the polarizers, (b) the light becoming noisy while passing through the birefringent plates and polarizers and (c) the need to create two separate beams, one divergent and the other convergent.

Comparison of the three alternate systems with the horizontal wet cell showed that the new vertical wet cell system need not be implemented because at best it shows no advantage over the horizontal wet cell. The quarter wave plates and polarizer system would be much more cumbersome than the horizontal wet cell. Also the recording would be "dirty" from scattering in the polarizers and quarter wave plates. The horizontal lens mirror could be better than the horizontal wet cell due to solid interference path and lower AR glass reflections, but the lens mirror system lacks the accommodation for construction of different R of C holograms, and will require a very large and expensive lens instead of a glass plate.

Light Requirements for Hologram Production

In order to produce a good sinusoidal grating, interference must take place at the emulsion. An acceptable fringe contrast is a requirement for this interference pattern. To meet this requirement, the two interfering wavefronts must be coherent.

Coherent light has two characteristics: temporal and spatial. Temporal coherence (narrowness of the wavelength spectrum of chromaticity) implies that the phase difference

of the interfering wavefronts be independent of time in the interfering region along the direction of propagation and spatial coherence, that the phase difference be constant in the interfering region across the direction of propagation. The visibility of the fringes limits the dimensions of the interference region. "Coherence length" defines the limits of the region or difference of the optical path of the two wavefronts where interference effects are no longer observable.

The illuminating light must be clean; that is, the diffraction patterns from dust on lens surfaces and surface reflections must be removed or they will be recorded on the hologram. These diffraction patterns can be removed by the spatial filter. The illuminating light intensity must be uniform over the exposure area. To insure uniform intensity the expander lens fills the entrance aperture of the M.O. with only the nearly uniform portion of the Gaussian intensity distribution of the expanded beam.

The best recording will take place when the ratio of intensities of the two interfering wavefronts are near unity. To insure a ratio close to unity, the elements after the spatial filter must absorb very little light. The master mirror must be made to reflect as much light as possible. The photosensitive emulsion must absorb the minimum of light compatible with the process.

Laser Requirements

To meet the temporal coherence requirements the laser must operate continuous wave at single frequency to maintain a coherence length of at least 20" (path difference is 18"). For good fringe contrast, a coherence length greater than the path difference is necessary.

The laser must operate in the TEM_{00} mode to meet the requirements of spatial coherence and uniformity across the illuminated area. These requirements are to be maintained during the long exposure time needed for hologram production.

Considering the power losses from sampling with the Fabry-Perot etalon, the beam-steering mirrors, other optical surfaces, and the losses due to using only the nearly flat portion of the Gaussian light distribution, the output power of the laser must be sufficient to initiate photo-reduction in the emulsion. The output power must also not be so small as to necessitate very long exposure times. The laser must

not be restrictive by its needs of electrical or cooling supply or by its size.

Performance of the 20-watt Argon Laser. A photometer was used to measure the output power at the plate (emulsion) site and to check the accuracy of the laser's power meter.

A scanning Fabry-Perot etalon was used to test output light for mode stability. The information from the etalon was analyzed on an oscilloscope. To test the information, interferometers were set up to compare laser stability. Long path difference interferometers were used to measure temporal coherence (coherence length). The coherence length of the laser was measured and found to be greater than 48" when operated at TEM₀₀. Observation showed the laser operating in this mode for periods in excess of 1 hour and possibly up to 24 hours.

The laser developed a maximum output power of 12 watts single line operation. With an intra-cavity etalon added for single mode operation, the single line output power was reduced by at least 50%. The output power was reduced further to insure continuous stable mode operation to 4 watts as a maximum at the 514.5nm line.

In summary, the laser, when operating properly, easily met the requirements for this project.

SECTION VI
FABRICATION OF A MOSAIC OF THREE
HOLOGRAPHIC PANCAKE WINDOWS

General Characteristics

Once the procedure for producing HSBM having an aperture of 24" x 21½" and a radius of curvature of 36.1" with good quality was established, production began on the final mirrors, for assembly in the three holographic Pancake Windows. In this section is described:

1. The production of the 21½ x 24" HSBM with the following characteristics:
 - a. A radius of curvature of 36.1".
 - b. A spectral response which will peak at a wavelength of 544nm (to match the P-44 phosphor of the CRT).
 - c. A diffraction efficiency as close as possible to 50%.
 - d. A half-width response not to exceed 30nm.
 - e. Good image resolution.
 - f. Acceptable uniformity and minimal cosmetic defects.
2. The alignment and cementing of the polarizers and quarter-wave plates.
3. The final assembly of the three holographic windows.
4. The trimming and cutting of knife edges for the best butting of the windows.

Production of the Final Holographic Mirrors

Spectral Response. The final HSBS mirrors should have a spectral response narrow enough to avoid dispersion effects and should peak at the same wavelength as the illumination sources, i.e., the CRTs with the P-44 phosphor. This P-44 phosphor has a very narrow spectral emission peak center at 544nm and has a half-width of about 3nm (Figure 19).

The formulation for the production of the final mirrors was calibrated to produce holograms which will peak after normal drying at a wavelength slightly higher than 544nm. Then, by a process of further dehydration, the response should be brought slowly down to reach the designed wavelength peak (Figure 20).

This approach was complicated because the spectral response of the holograms does not reach a final state but instead, reaches a state of equilibrium which is a function of the environmental parameters especially humidity.

When the holograms are cemented with a cover plate or between other elements, as in the Pancake Window configuration and consequently insulated from humidity variations, then the holographic response will reach a final state which is, between limits, unknown a) with regard to the amount of the displacement of the wavelength peak and b) the duration of this displacement until it reaches the final state.

The result of an experimental Pancake Window assembly (using mineral oil as an optical refractive index match instead of a permanent optical cement) demonstrates that any displacement of the holographic spectral response from the 544nm, will translate into a lowering of the HPW transmission. For example, considering a hologram with a bandwidth spectral response of 30nm and center at 544nm and with an ideal diffraction efficiency of 50% at the peak, then a displacement of the peak of 5nm will mean approximately a 10% loss in transmission; a displacement of 10nm results in a loss in transmission of 75%; and no transmission at all for a displacement larger than 15nm.

The second result in analyzing the experimental HPW was a serious displacement of the wavelength peak with relation to large field-of-view angles (Figure 21). At 20° off-axis, this displacement could be as large as 10nm, producing a loss of transmission of about 75%. Consequently, this effect caused an unacceptable darkening of the HPW edges, most noticeable in a mosaic of windows assembly

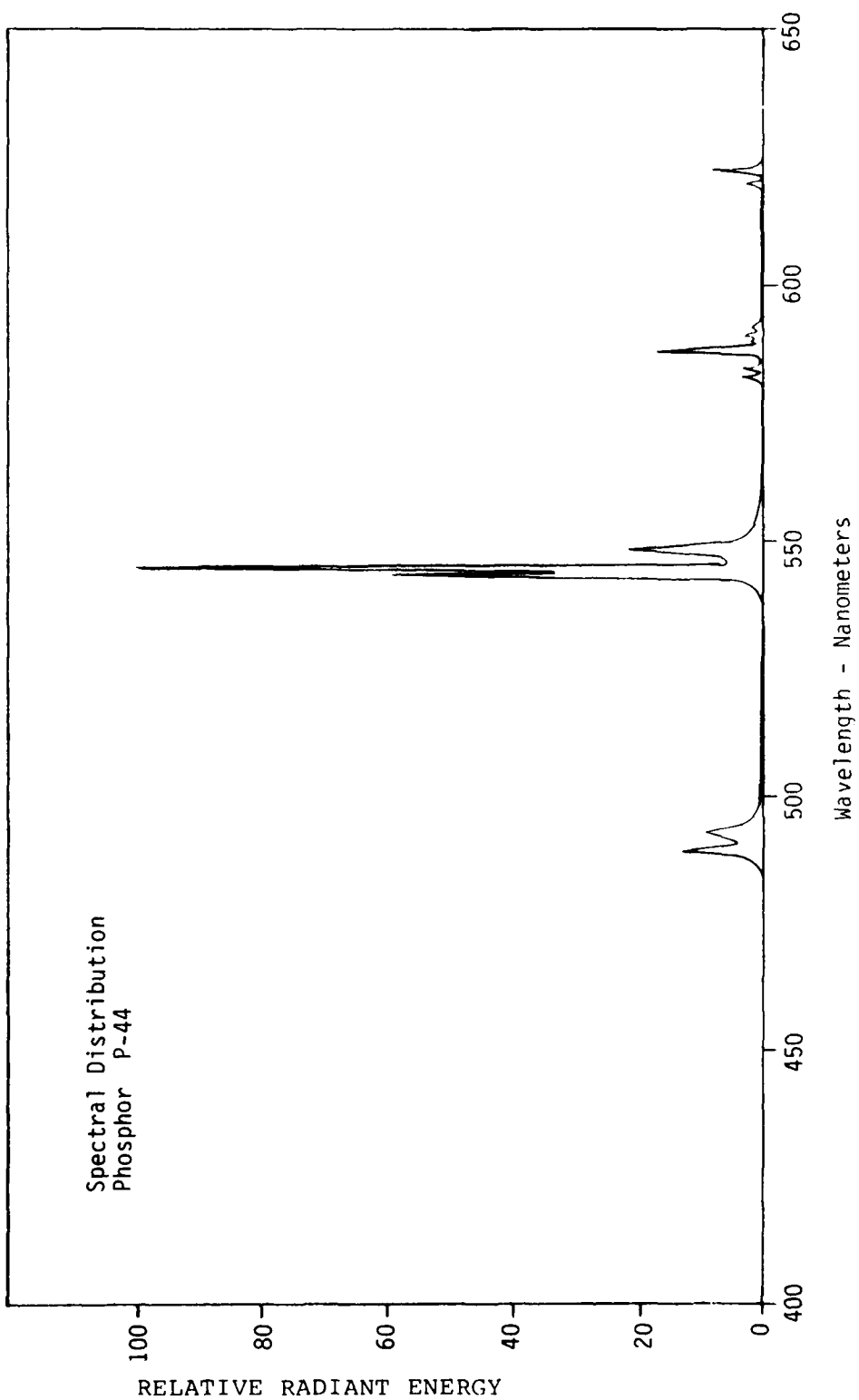


Figure 19 Spectral-Energy Emission Characteristics
of Phosphor Type P44

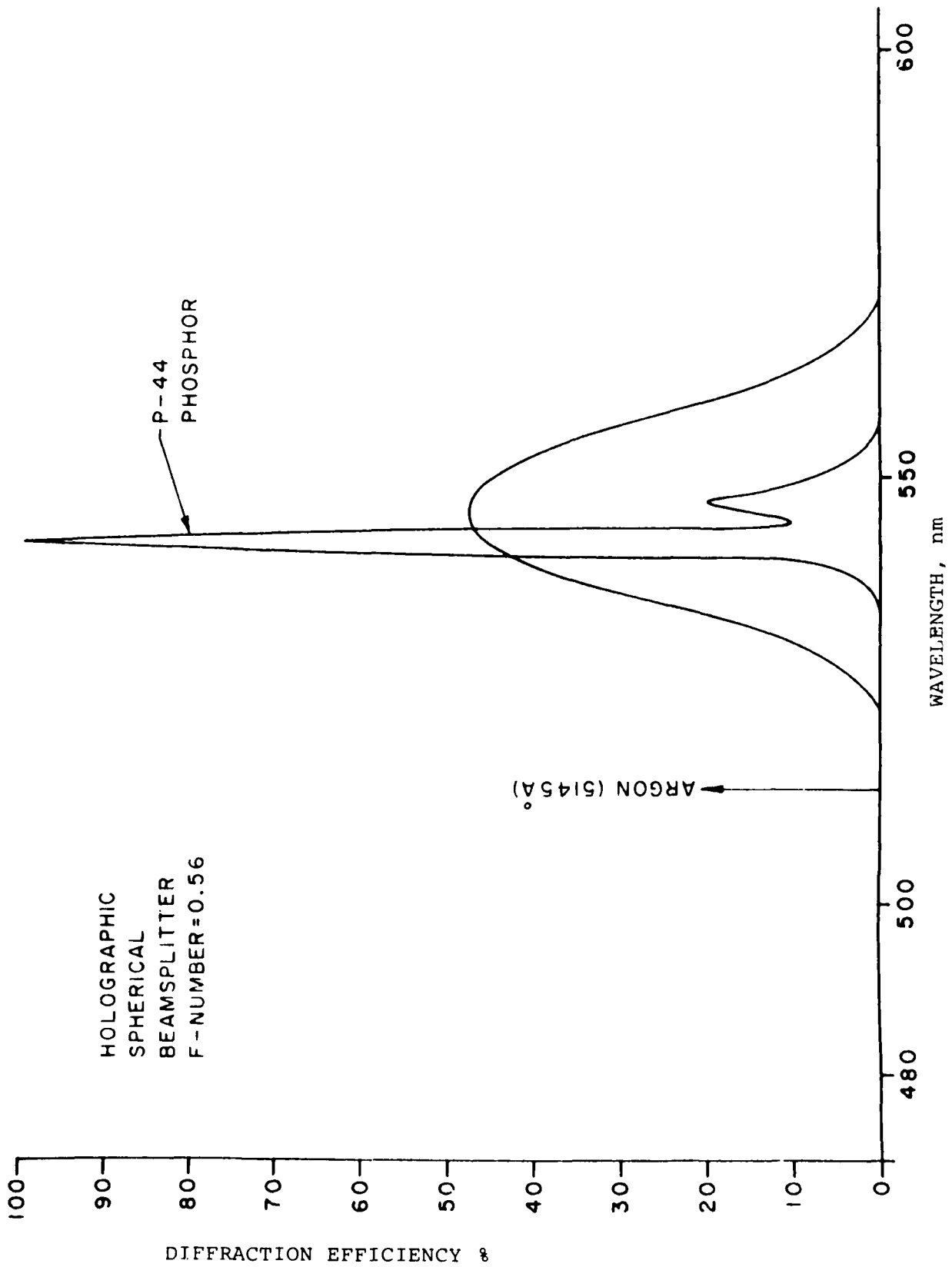


FIGURE 20. P-44 PHOSPHOR AND HOLOGRAM
SPECTRAL DISTRIBUTION

GEOMETRY:

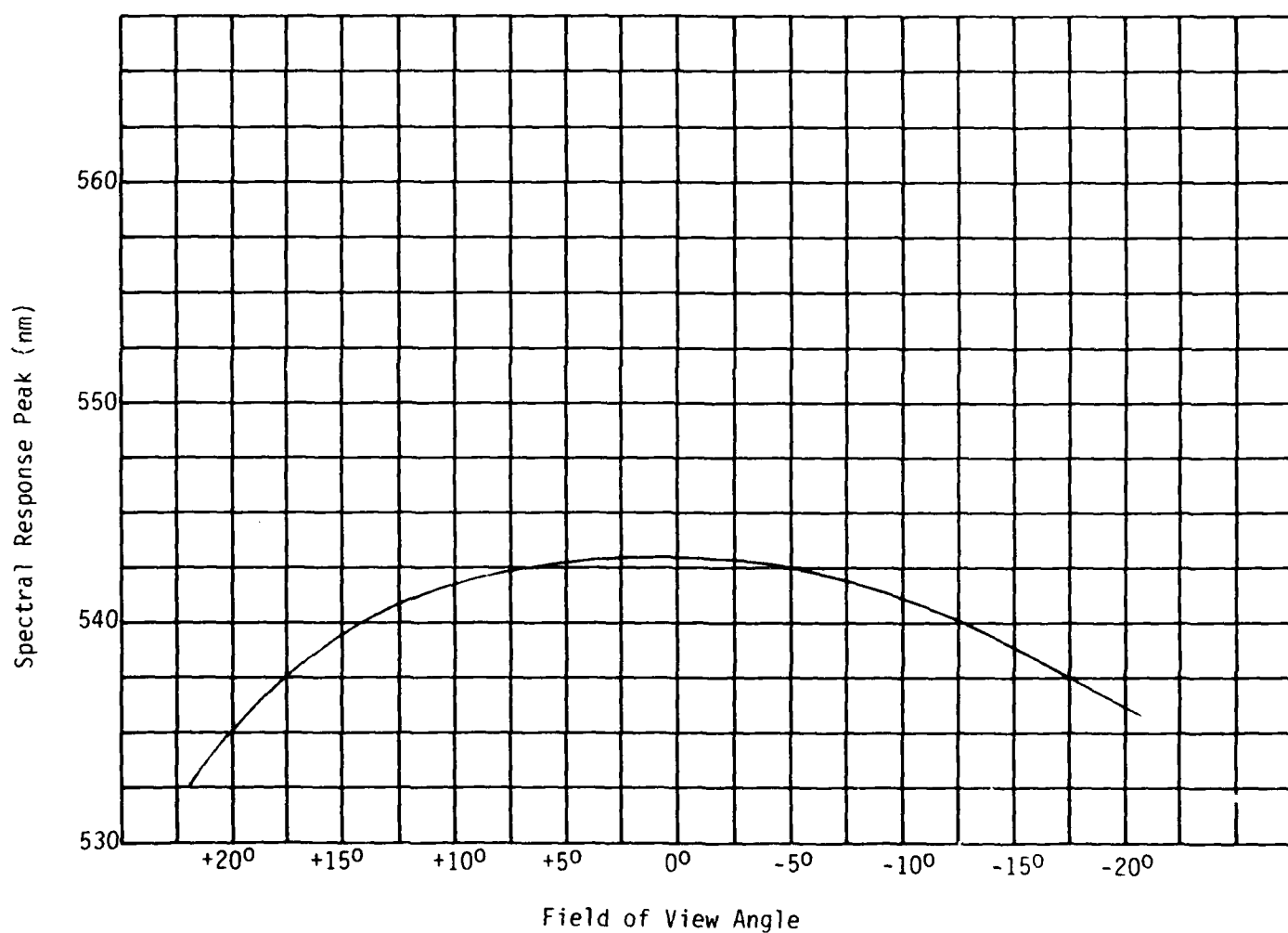
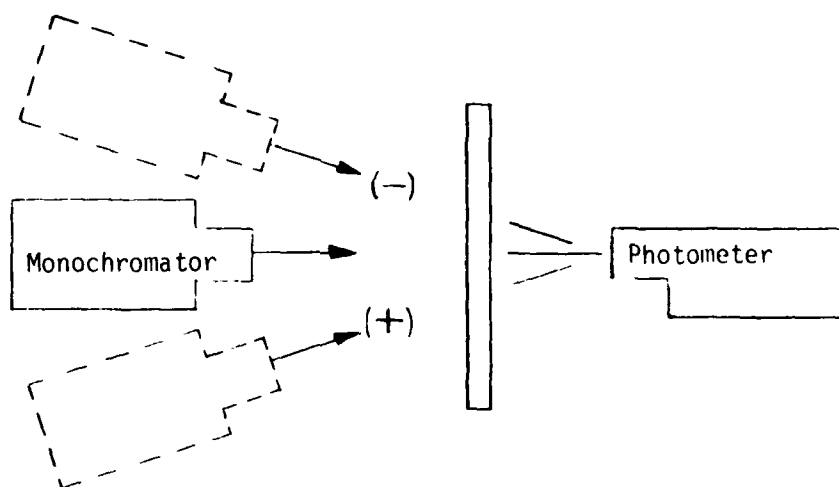


FIGURE 21 SHIFT OF THE SPECTRAL RESPONSE PEAK VS. FIELD ANGLE
IN #1 HOLOGRAPHIC PANCAKE WINDOW (ASSEMBLED IN OIL)

where the brightness will be maximum at the center of each window and minimum to none at the areas close to the joints.

The reason for the displacement of the hologram spectral response peak with the angle of incidence is the lack of conservation of Bragg angles in the hologram reconstruction. The Bragg angle is designated as the angle each beam makes with the fringe plane in the medium during construction (exposure to coherent laser radiation). When the hologram is illuminated during reconstruction (working as a holographic mirror) for angles of incidence coincident with the Bragg angle, the diffraction efficiency will be maximum and no spectral displacement will occur. Although the holographic mirrors are constructed and used as spherical mirrors, the angles of construction are unique and correspond to the illumination from a point source placed at a point which will become the center of curvature of the holographic spherical mirror. The angles of reconstruction (when the holographic mirror is used in the Pancake Window configuration) correspond to an illumination source placed at half the distance (at the focus), and not only at the focus, but over the focal plane.

A third observation of this experimental window was the accentuation of local nonuniformities when the window was illuminated with the narrow P-44 phosphor. Variation in hardness of the gelatin film (related to defects in the manufacturing of the film, to lack of uniformity of the illumination when the hologram was constructed and to nonuniformities in the chemical developments) produces areas in the hologram which will diffract at slightly different wavelength peaks. Again, depending on the displacement from the 544nm peak, the transmission of the holographic window throughout these areas will vary and will greatly emphasize these defects.

Two solutions were proposed for the problems caused by the spectral shift. With one solution the problems are eliminated using a broad-band phosphor in place of the P-44 narrow phosphor. With the other solution, the problems are corrected or reduced by placing the hologram spectral response not at the 544nm (P-44 phosphor wavelength peak) but at other values from which the spectral shift could be average with respect to the P-44 phosphor.

The use of a wider phosphor (P-31 type) was implemented, and the P-44 phosphors were replaced. The broad-band spectral emission provides very large tolerances for the location of the hologram spectral response peak. The transmission of the window remains practically constant

for small displacements $\pm 10\text{nm}$, and the variation for the very large shift is unnoticeable. This new phosphor has a half intensity bandwidth of over 90nm , or about three times wider than the hologram spectral response. Consequently, the efficiency of the illumination is poor, and the holographic window is transmitting a third of the spectral input of the illuminating source. No readily available phosphor has a spectral response wider than the P-44 but narrower than the P-31.

The other solution was tested and proved to be valid but was not implemented because it requires tight tolerances in the location of the hologram peak response, and there was insufficient time to improve the required technique. Basically, this solution calls for placing the spectral holographic response peak at a higher wavelength (toward the red) than 544nm . If the field of view required is, for example, 60° and the shifting at 30° off-axis is 15nm toward the blue, then the hologram peak for the on-axis response will be placed at $544\text{nm} + (15/2)\text{nm} = 551.5\text{nm}$. The hologram also will have a diffraction efficiency higher than 50%, but because of the very narrow spectral bandwidth of the P-44, the Pancake Window would not separate into two images the two transmission maxima which will be separated by only 2nm .

The combination of centering the P-44 phosphor at the middle of the holographic spectral shift and using a hologram with a diffraction efficiency higher than 50% produces a HPW transmission variation across the field of view which will be between the specifications (Figure 22). For example, at $544\text{nm} + 7.5\text{nm} = 551.5\text{nm}$, the spectral response of the hologram will cross the P-44 spectral peak at around the 40% diffraction efficiency and the transmission of the window will be, let us say, 1%. The same will occur for the extreme field-of-view angles $544 - 7.5 = 536.5\text{nm}$, where also the spectral response of the hologram will cross the P-44 at the 40% diffraction efficiency. Between the center of the field-of-view and the extreme field-of-view angles, the hologram will cross the P-44 at the 60% diffraction and the transmission of the window will also be 1%. Between these three points (the center, the middle, and the extreme of the field of view), the hologram spectral response will cross at 50% diffraction efficiency and the transmission of the window will be 1.04% or 4% higher, which will be quite acceptable.

The advantage of this technique, is that, by using the narrow P-44 phosphor, all of the available illumination

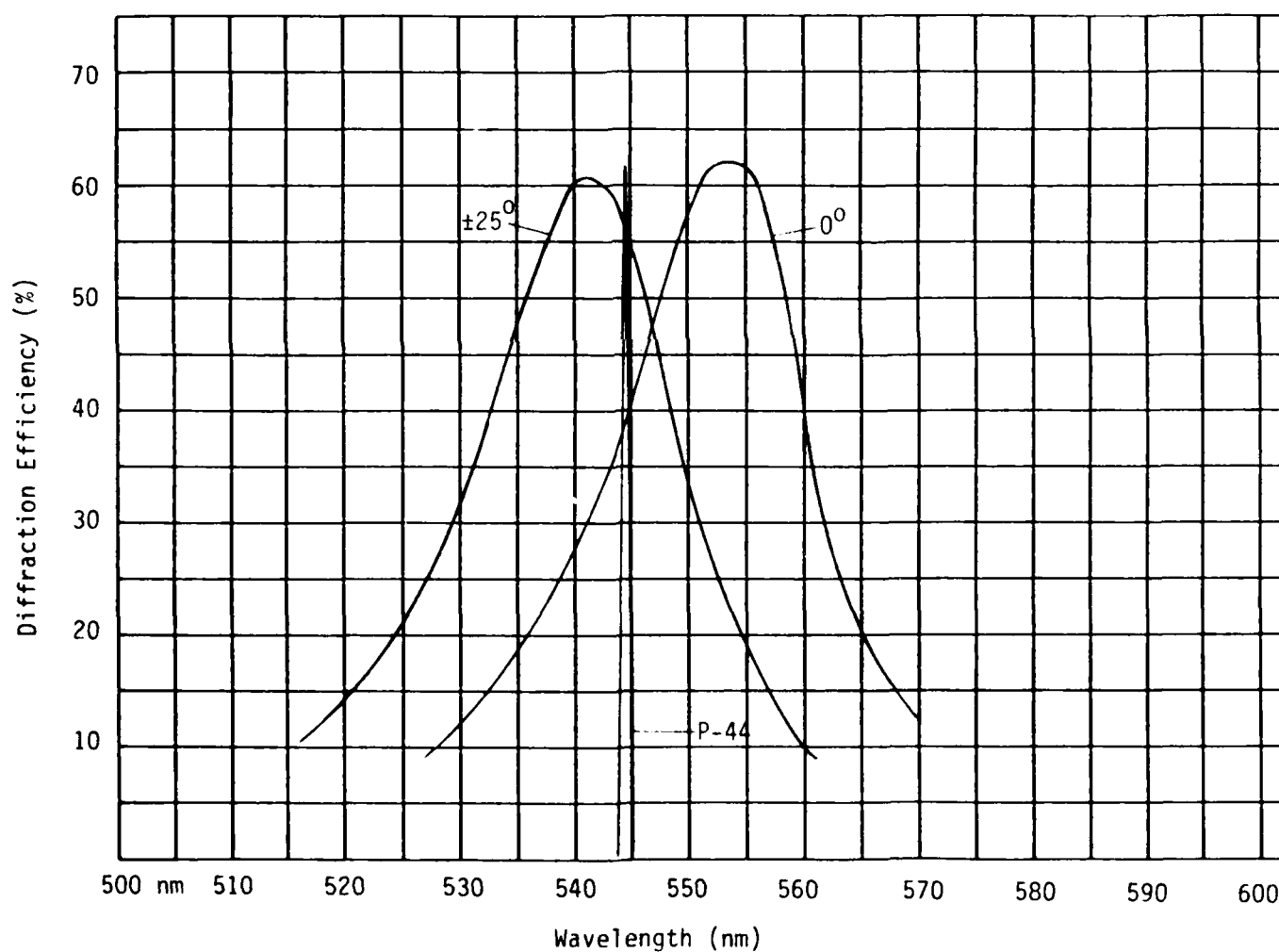


FIGURE 22 SPECTRAL RESPONSE OF A HOLOGRAPHIC SPHERICAL BEAM-SPLITTER AT 0° AND $\pm 25^\circ$ FIELD-OF-VIEW ANGLES AND SPECTRAL DISTRIBUTION OF P-44 PHOSPHOR

light will be used by the Pancake Window. Also, the absolute transmission will be at least three times higher than the transmission with the wide P-31 phosphor.

Diffraction Efficiency

The use of the implemented P-31 wide band phosphors required that the diffraction efficiency of the HSBS mirrors not be higher than 50% to avoid doubling of the images as previously explained. If a useful hologram has a diffraction efficiency higher than 50%, it is reduced by redeveloping the hologram again and increasing the chemical hardening treatment. This consists of immersing the hologram in water until the holographic wavelength response is raised and then in a solution of sodium bisulfate (hardener). The concentration and duration of the bath is a function of the lowering in diffraction efficiency desired. Because the process could be repeated without deterioration of the hologram, it is possible to calibrate the process with the same hologram. After the hardening bath, the hologram is washed and dehydrated in the standard procedure.

A large reduction in diffraction efficiency could also produce a shift in the spectral response peak of the hologram. Large values in diffraction efficiency usually are caused by voids and cracks which develop at the diffraction planes. These voids and cracks are also responsible for a permanent swelling of the gelatin film or an increase in the separation of the diffraction planes. A strong hardening of the gelatin film during redevelopment may fuse some of the cracks and voids, shrinking the film causing a reduction in the spacing of the planes and, consequently, a shifting of the spectral response toward the blue. Generally, this effect is more dependent on the cracks than on the voids.

Resolution

The resolution of the final HSBS mirrors varies with the spectral response of the hologram, field-of-view angles, position in the exit pupil, and local areas in the holograms. In general, the resolution was considered very good for on-axis angles and for sight directions which crossed the center of the hologram. The resolution generally worsened for large field-of-view angles and large observation pupils, but not always, since resolution as good as on-axis was observed in discrete areas with extreme field-of-view angles and extreme pupil displacement.

It was observed that the resolution was better during the first several hours of drying after development when the spectral response peaked at higher values. The resolution worsened as the hologram approached its permanent dry state and its spectral response peaked at lower wavelength values. The worsening of resolution in local areas of the hologram correlates with cosmetic defects usually produced by nonuniform illumination and by unevenness in the production or development of the film.

The factor contributing most to the loss of resolution is believed to be the local variation of hardness related to these cosmetic defects. At the extreme in which the film becomes so soft that it reticulates, the loss of resolution is complete.

Cosmetic Defects and Uniformity

During this program, holographic facilities were built and techniques developed to produce very uniform holograms with practically no cosmetic defects. It was regrettable that these techniques could not be used in the production of the final holograms because of time constraints. Also, concentration on other problems, such as spectral response, and diffraction efficiency did not permit a slow and careful production of the films using the more refined techniques developed during this project. Cosmetic defects and non-uniformities could be ignored as irrelevant in the testing of the mosaic HPW for feasibility and with the exception of resolution also for optical performance.

Assembly of Each Holographic Pancake Window

Each of the three HPWs were assembled in a single rectangular package 21½" x 24". The package comprises several elements cemented together with optical cement (Figure 23). It consists of (from the illuminating source or CRT side): (a) a cover plate with high efficiency AR glass, (b) a linear polarizer with its axis parallel to the longest side of the rectangular (horizontal side), (c) an HSBS mirror with the positive side toward the observer, (d) a quarter-wave plate with its retardation axis at 45° clockwise with respect to the first polarizer axis, (e) a plane beamsplitter glass mirror with its coated side facing the CRT, (f) a quarter-wave plate with retardation axis at 135° clockwise with respect to the first polarizer axis, (g) a second linear polarizer with its linear axis

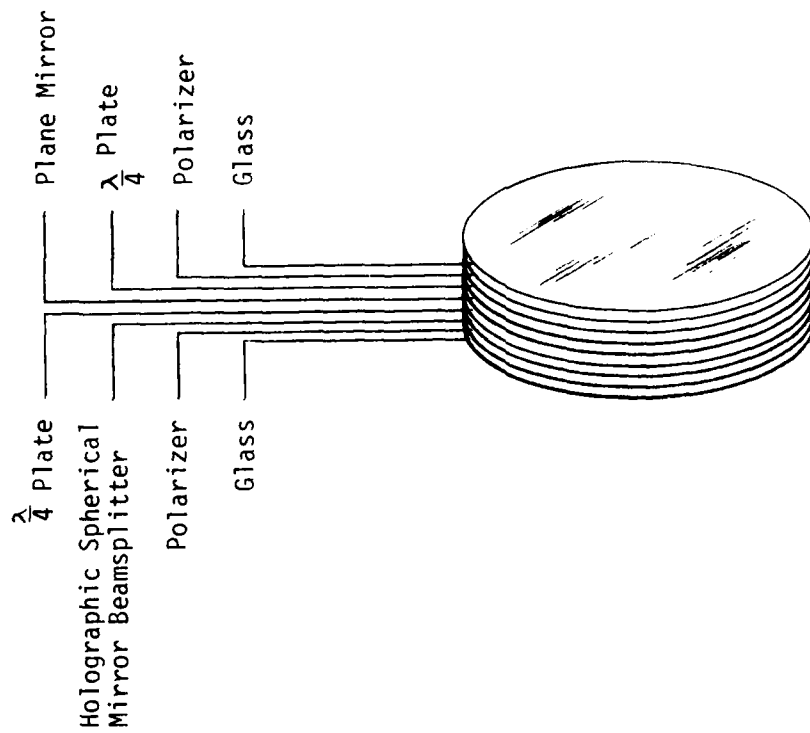


FIGURE 23. HOLOGRAPHIC PANCAKE WINDOW PACKAGE

rotated 90° with respect to the first linear polarizer axis, and (h) a cover plate glass with high efficiency AR coating.

The glasses in the Pancake Window package are $1/8$ " thick except for the HSBS mirrors which are $1/4$ " thick. The thickness of each polarizer is 0.006" and of each quarter-wave plate 0.0012". The optical cement has a refractive index of 1.5 and is clear and strain-free when in solid form after being cured. Due to the restricted width of the polarizer material presently available, each of the mentioned linear polarizers is seamed. The seams were placed so as to provide minimum disturbance in the HPW mosaic configuration. The alignment of the polarizers and quarter-wave plate elements is first approximated geometrically and finally photometrically in the cementing operation.

Mosaic Configuration

The three produced HPWs were assembled in a mosaic configuration (Figure 24). This arrangement will provide a horizontal field-of-view of 120° by 40° vertical. The joining of the windows was glass to glass, and in a dynamic display, the transition of an image from window to window is not noticeable.

The odd shape of each window with discontinuous straight sides prevents the use of conventional techniques in cutting the edges of these windows. So, the windows were cut to shape using a sand blasting machine. To prevent damage to the cover plates, the windows were covered with adhesive rubber, and the cut was made through it. The cut produced with the sand blaster produced a finish that was acceptable for the sides that will not be butted together. A diamond blade in a milling machine was used to cut the straight edges of the sides that were to be joined. Mineral oil was used as the cooling fluid in the milling process to prevent any possible water contamination to the edges of the hologram.

SECTION VII

PERFORMANCE OF THE HOLOGRAPHIC PANCAKE WINDOWS

A total of four HPWs were assembled. The first one assembled had an HSBM that was intended to be used with the narrow P-44 phosphor. Its relatively poor performance dictated the manufacture and assembly of the other three HPWs to be used with a wider spectral distribution phosphor P-31. An experimental HPW was also provisionally assembled to evaluate the performance of a HPW and P-44 phosphor system with a better designed HSBM.

First Assembled HPW

The spectral response of the HSBM which was selected to be assembled in the #1 HPW is shown (Figure 25). Its spectral peak is not centered to the P-44 phosphor spectral distribution but is close enough to produce (on-axis) an acceptable transmission for the HPW.

In an experimental assembly of this HPW with oil instead of optical cement the spectral peak of the hologram shifted with the angle of incidence of the illumination (figure 26) and with the angle of field-of-view (Figure 21). Considering the narrow spectral distribution of the P-44 phosphor, this shift produces a severe loss of transmission at large field-of-view angles. At a 20° field-of-view angle, the transmission fell to 0.6% from a value of 1% on-axis.

In the process of being assembled with cement, the spectral response of the hologram shifted to a lower wavelength (Figure 27). The result was a poor transmission on-axis and no transmission at all at the extreme angles of the field-of-view. The shift of the spectral peak of this first HPW assembled permanently with optical cement is shown (Figure 28) with respect to angles of illumination and with respect to field angles (Figure 29).

Also measured (Figure 30) was a shift of the spectral response peak with respect to the eye position in the volume

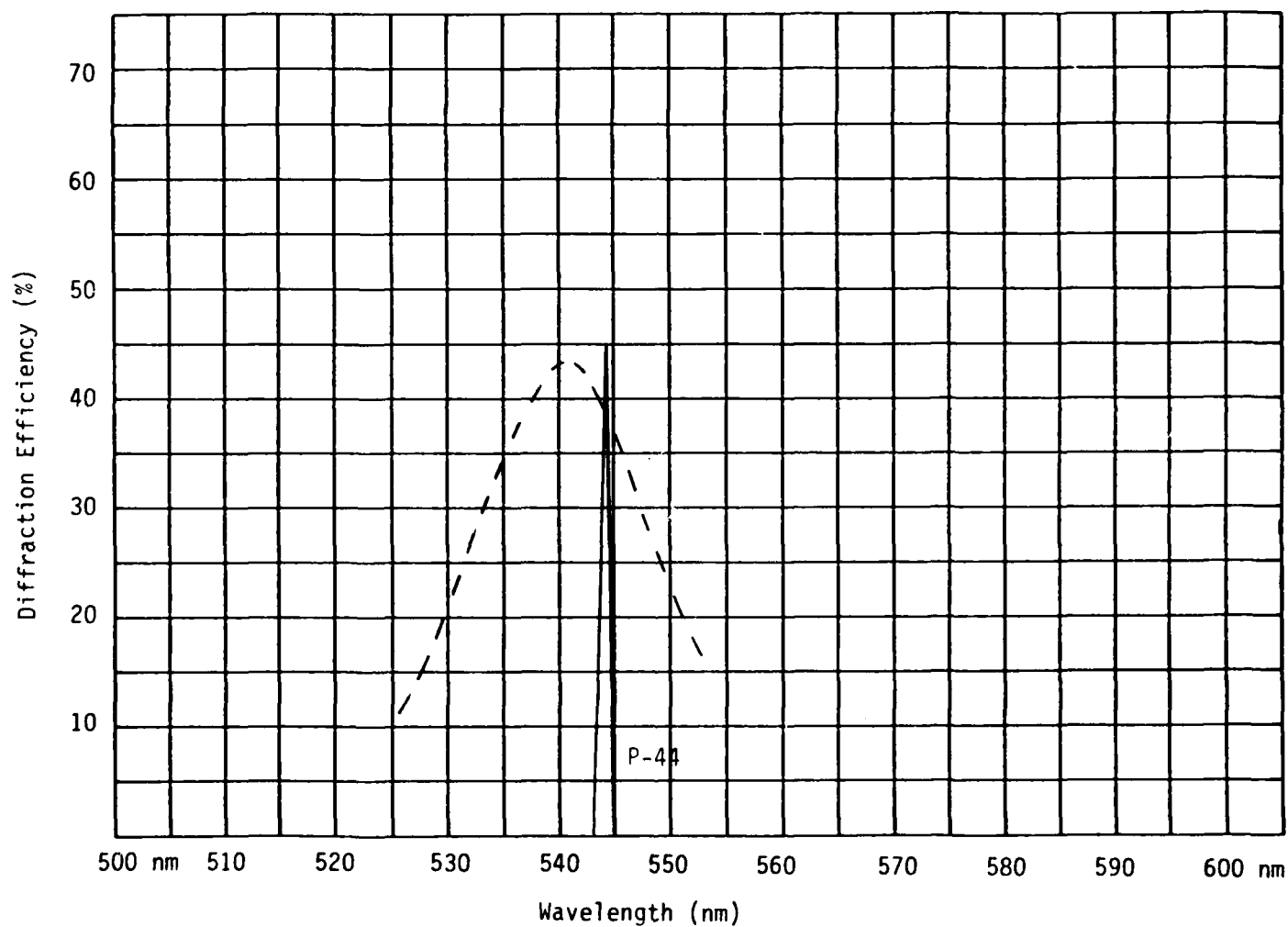


FIGURE 25 SPECTRAL RESPONSE OF THE HOLOGRAPHIC SPHERICAL BEAMSPLITTER USED IN THE #1 HOLOGRAPHIC PANCAKE WINDOW AND P-44 PHOSPHOR SPECTRAL DISTRIBUTION

GEOMETRY:

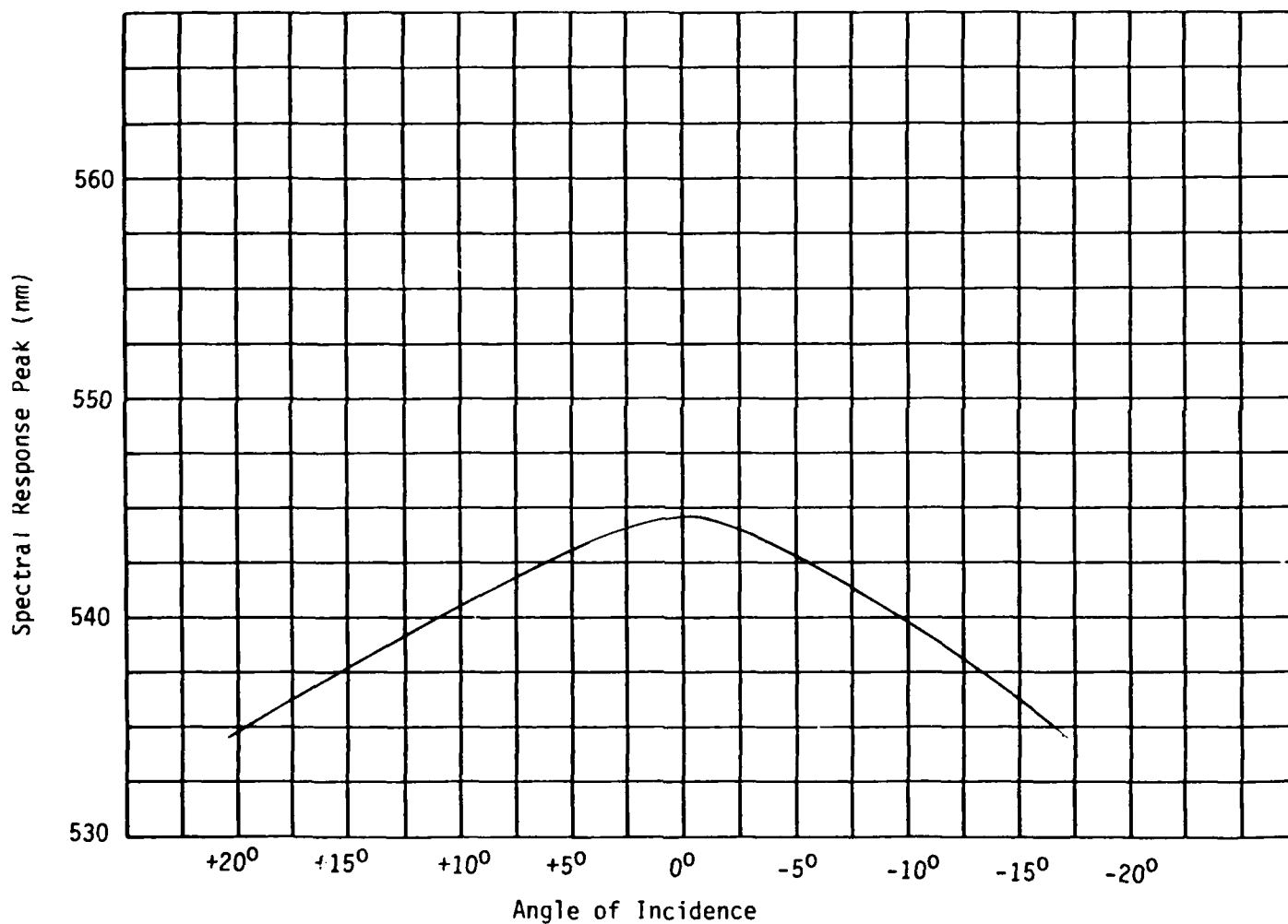
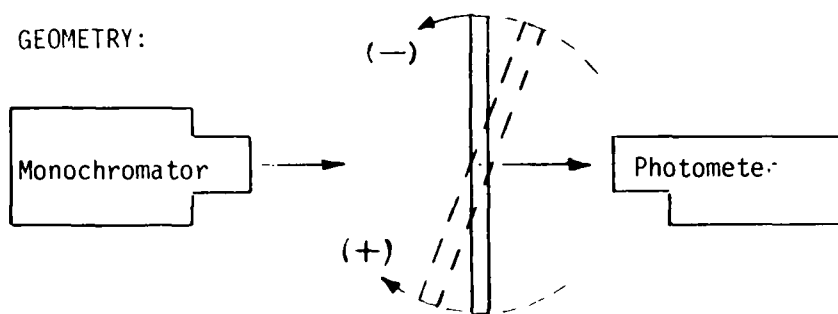


FIGURE 26 SHIFT OF THE SPECTRAL RESPONSE PEAK VS. ANGLE OF INCIDENCE IN THE #1 HOLOGRAPHIC PANCAKE WINDOW BEFORE BEING CEMENTED (ASSEMBLED IN OIL)

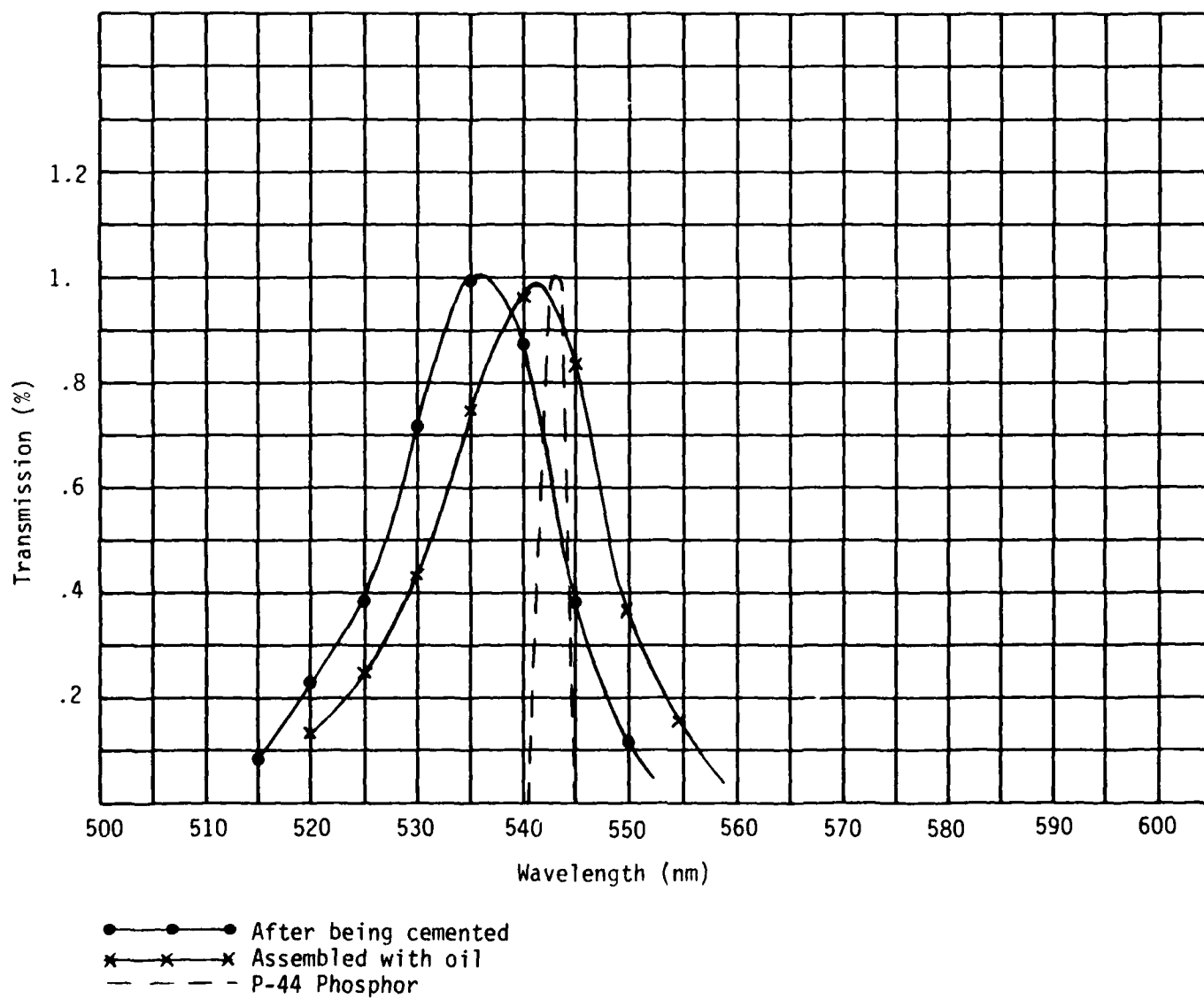


FIGURE 27 TRANSMISSION OF #1 HOLOGRAPHIC PANCAKE WINDOW
VS. WAVELENGTH

GEOMETRY:

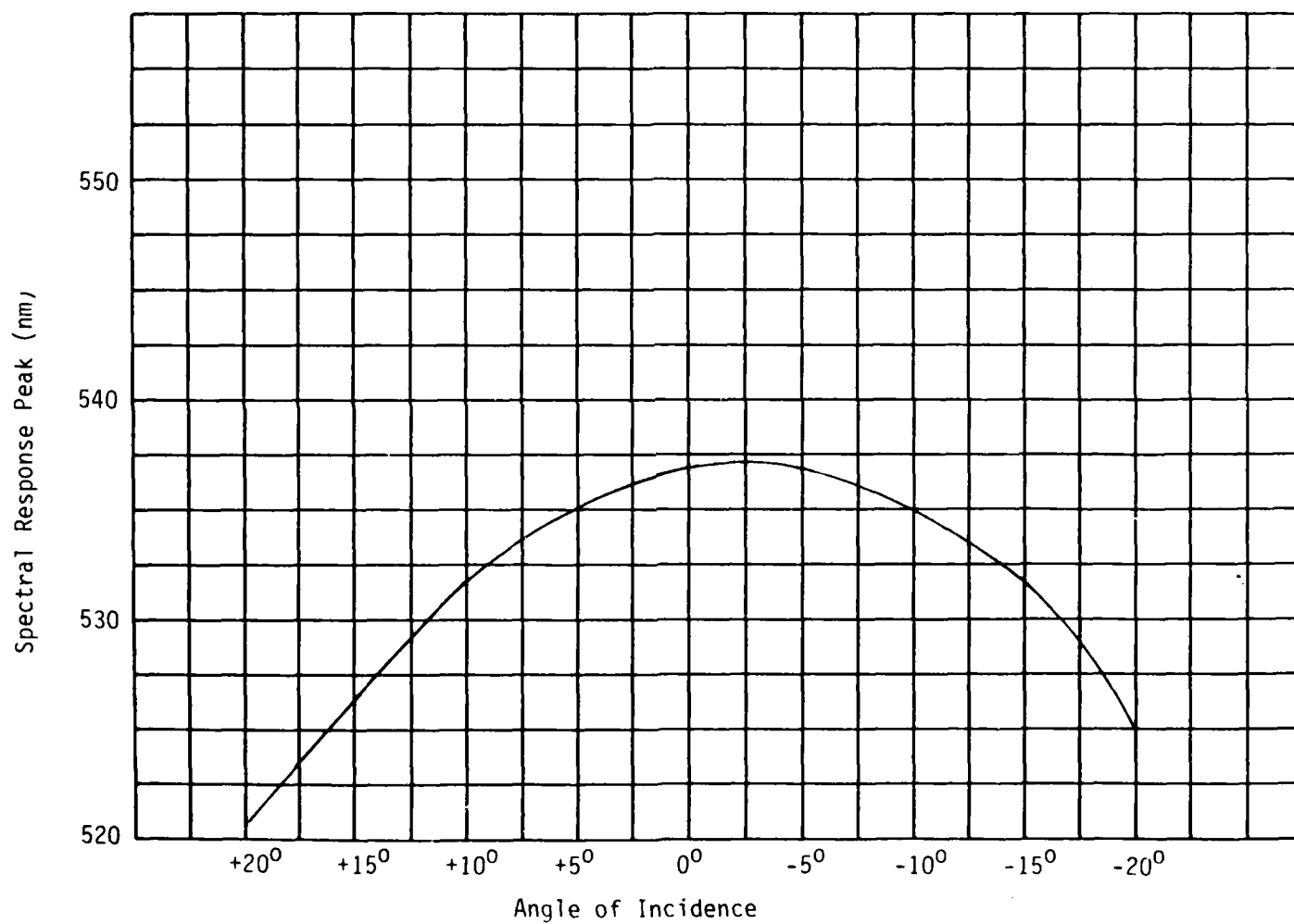
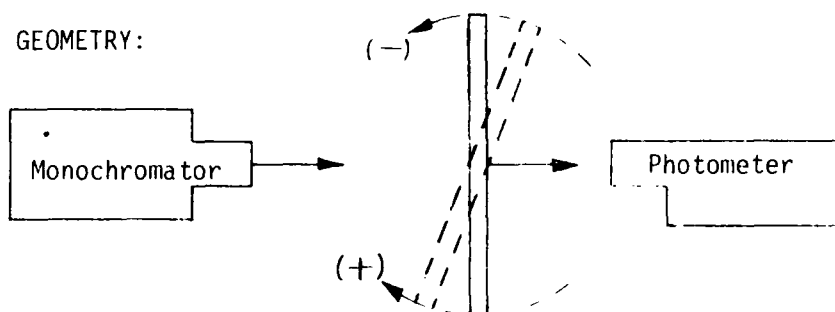


FIGURE 28 SHIFT OF THE SPECTRAL RESPONSE PEAK VS. ANGLE OF INCIDENCE:
HOLOGRAPHIC PANCAKE WINDOW #1 AFTER BEING CEMENTED

GEOMETRY:

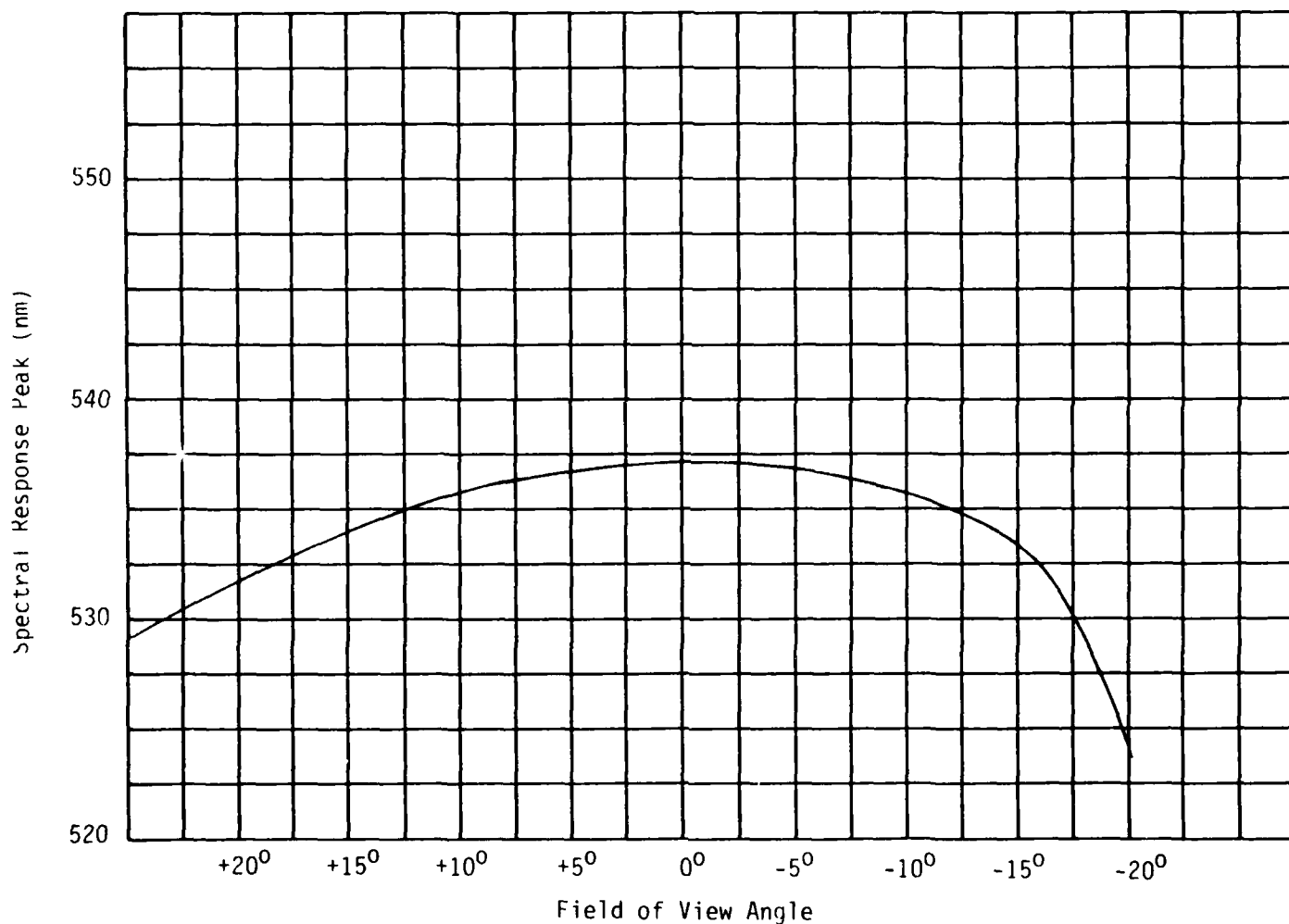
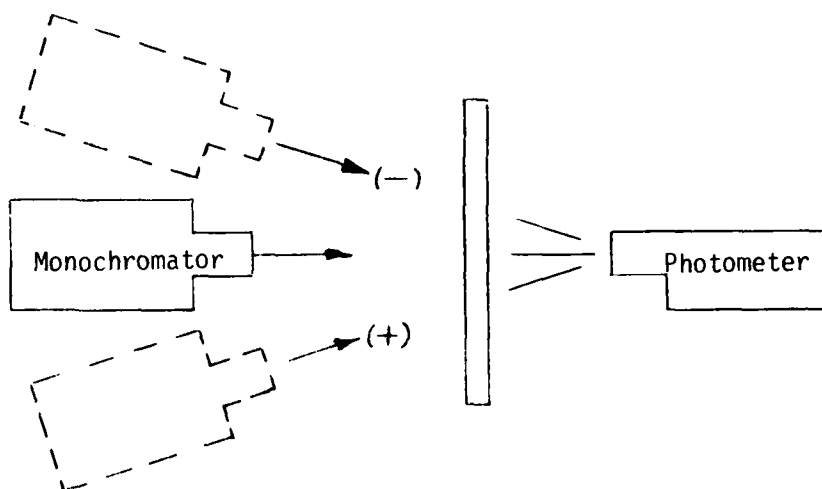


FIGURE 29 SHIFT OF SPECTRAL RESPONSE PEAK VS. FIELD OF VIEW ANGLE
HOLOGRAPHIC PANCAKE WINDOW #1 AFTER BEING CEMENTED

GEOMETRY:

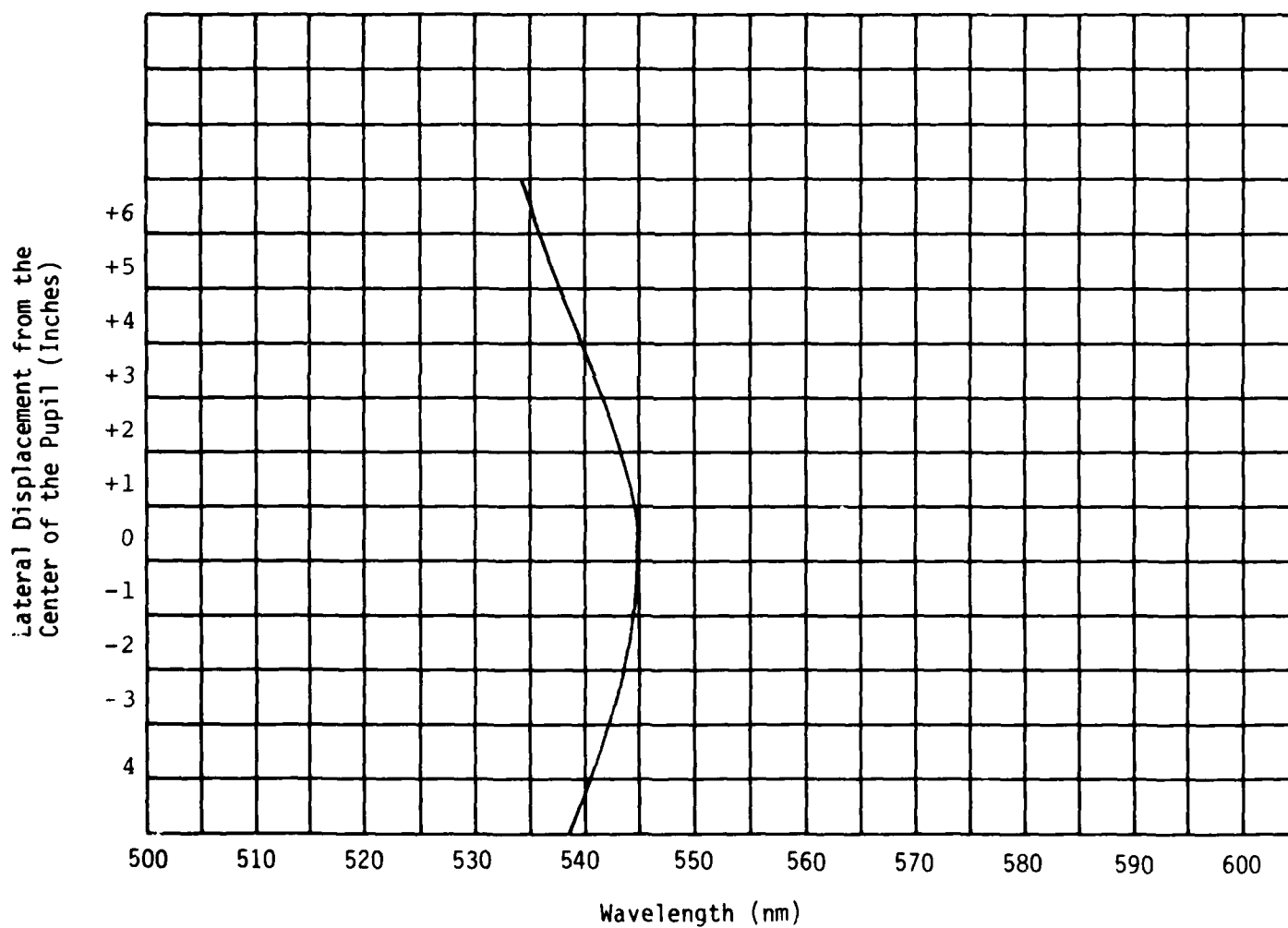
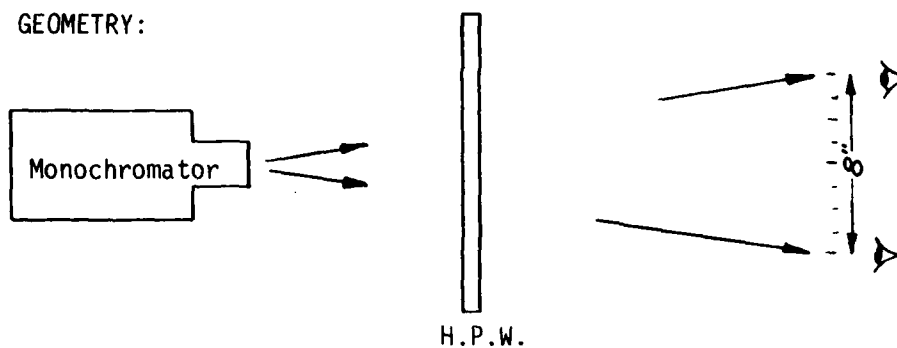


FIGURE 30 WAVELENGTH SHIFT VS. PUPIL POSITION
HOLOGRAPHIC PANCAKE WINDOW #1

of the pupil. For a pupil of 8" (+4" from the axis), the observed shift was about 5nm, which is quite acceptable.

Mosaic Configuration

As mentioned in Section VI, two solutions were proposed to overcome the problem of total loss of transmission found in the first (#1) assembled HPW. One solution was to replace the P-44 narrow band phosphor (Figure 19) of the CRTs with the P-31 wideband phosphors (Figure 31). This solution was implemented for the final windows. The second solution will be described and evaluated later.

In the mosaic configuration the three HPWs designated as left, center, and right windows, as viewed from the observer side. The diffraction efficiency of the holograms (HSBM) used in the center, left and right windows are plotted (Figure 32) as a function of the wavelength. As explained earlier, the use of wide band phosphor imposed the restriction of a diffraction efficiency smaller than 50% to avoid a spectral double peak in the HPW transmission. Originally, these plates had a diffraction efficiency well over 50%, which was reduced to the plotted values with a redevelopment process. The spectral peak around 560nm was selected because: (a) it is close to the photopic spectral peak, (b) a better resolution performance was observed at higher than at lower wavelengths with these particular holograms, (c) a small shift to lower wavelengths after being assembled was expected. The transmission of the left, center, and right HPWs is shown in Figure 33 as a function of the wavelength of the illumination. It is noted that a shift of the holograms to a lower wavelength had taken place after being cemented. The holograms continued shifting to even lower wavelength as shown in Table 3. The shifting of the spectral peak after the hologram has been cemented is not a normal occurrence. The shift probably occurred in this case because (a) the holograms were redeveloped a few times to lower their diffraction efficiency and (b) because a better resolution performance had been observed when the holograms were responding at higher wavelengths (not completely dried), they were cemented at this stage, with the expectation that the shift could be stopped. The natural response of these holograms when dried for a few hours was the same as that achieved several months after they were cemented when not quite dry. If the plates are cemented when dry, an observable wavelength shift should not appear.

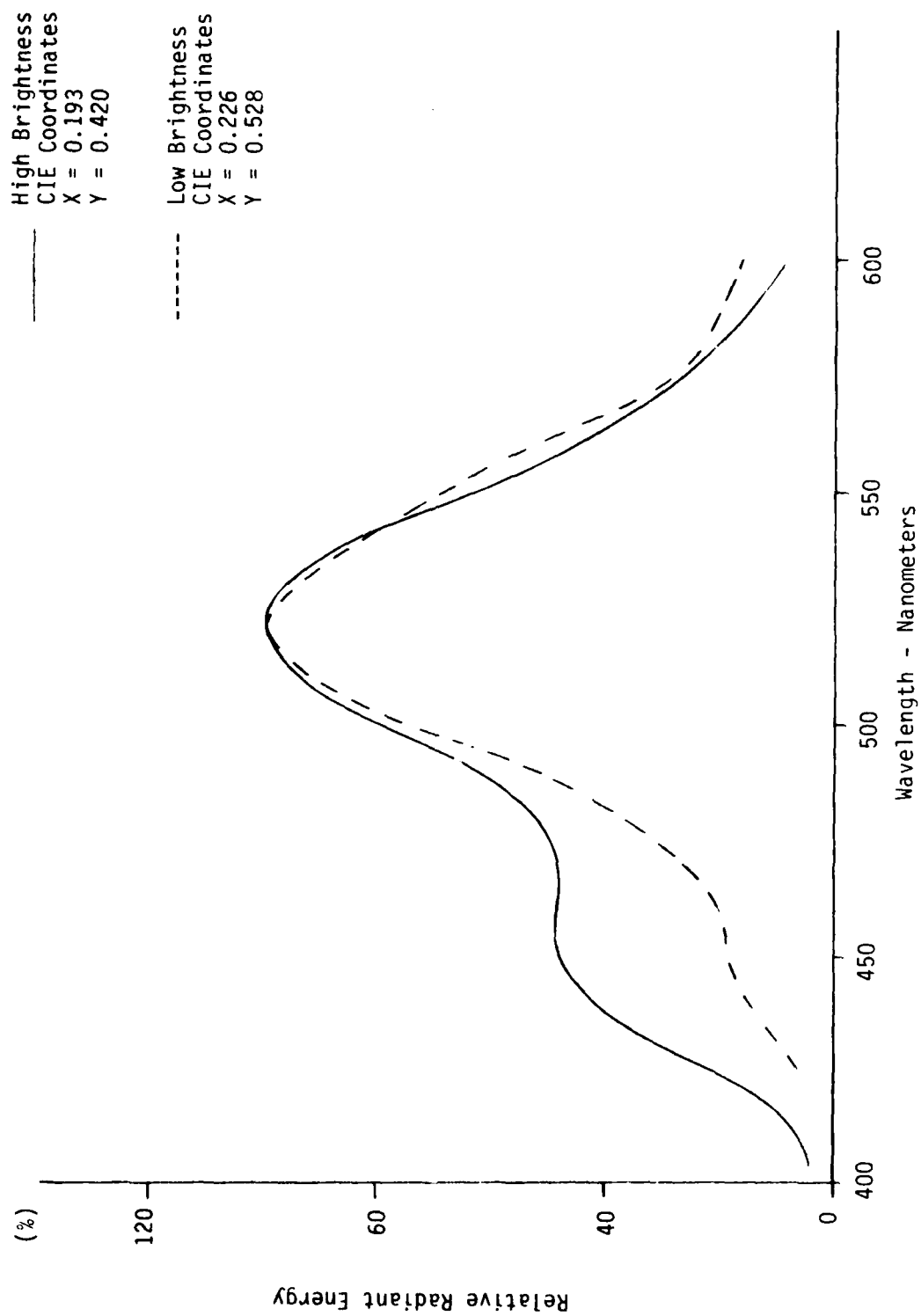


Figure 31 Spectral-Energy Emission Characteristics of Phosphor Type P31

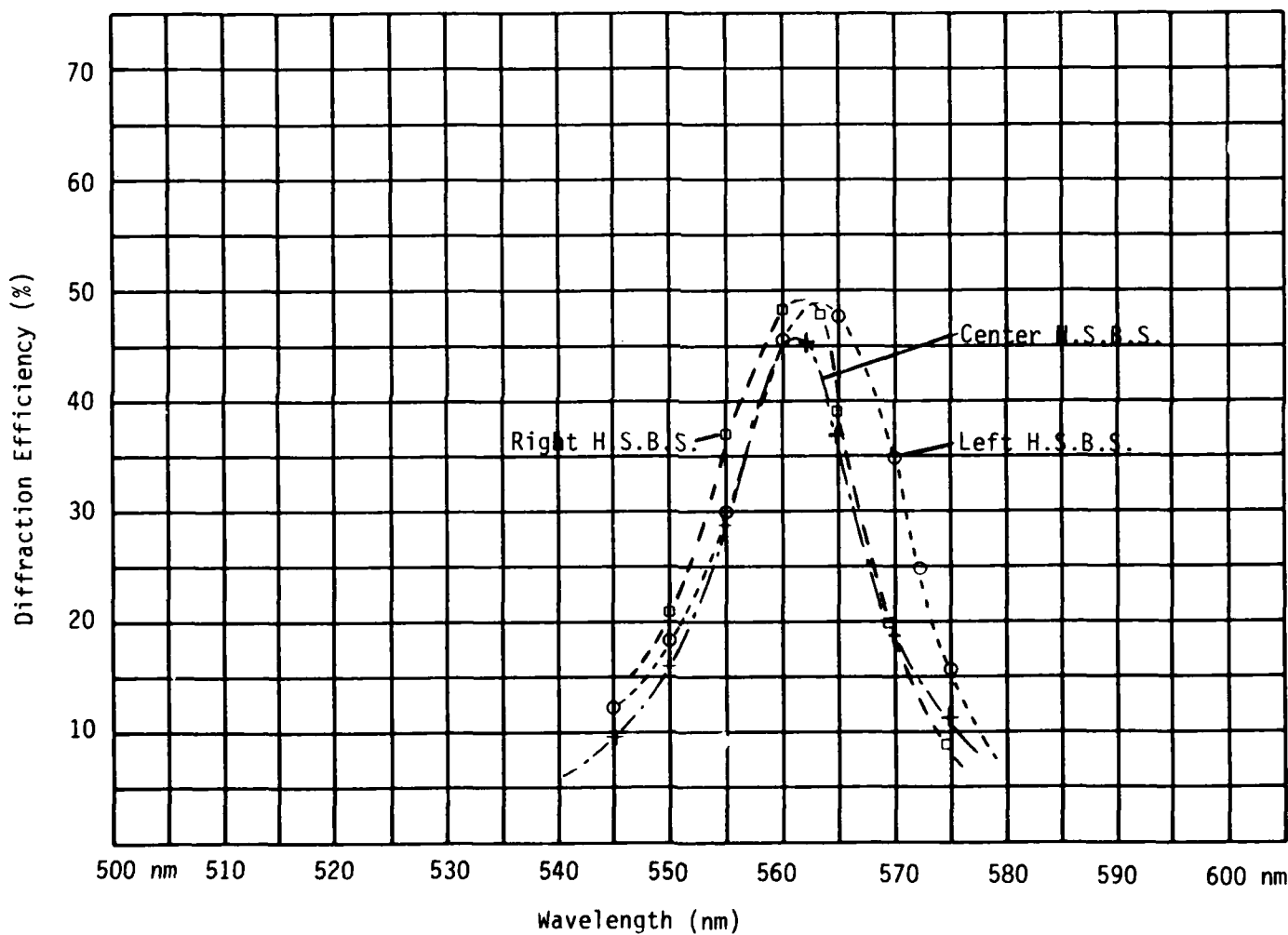


FIGURE 32 DIFFRACTION EFFICIENCY VS. WAVELENGTH OF THE HOLOGRAPHIC SPHERICAL BEAM SPLITTER USED IN THE RIGHT, CENTER AND LEFT HOLOGRAPHIC PANCAKE WINDOWS

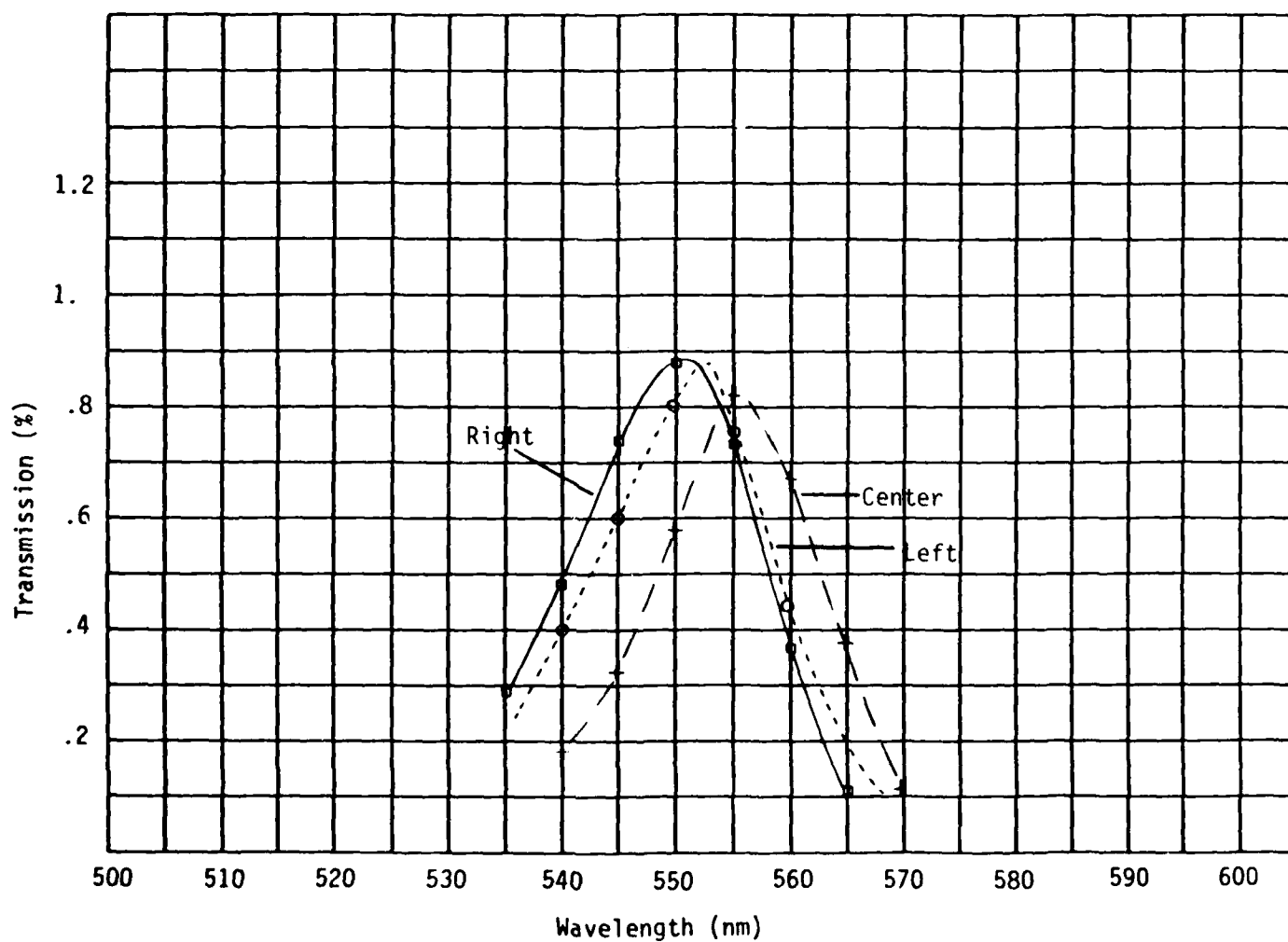


FIGURE 33 TRANSMISSION VS. WAVELENGTH FOR THE CENTER, RIGHT AND LEFT HOLOGRAPHIC PANCAKE WINDOWS IN THE MOSAIC CONFIGURATION

Table 3. SPECTRAL SHIFT VS. TIME

Holographic Pancake Window	Holographic Mirror Before Being Cemented	Holographic Mirror After Being Cemented in the HPW Confirguration		
	Mar 78	Apr 78	Jun 78	Nov 78
Left HPW	563 nm	552 nm	542 nm	535-537 nm
Center HPW	561 nm	553 nm	548 nm	541-543 nm
Right HPW	562 nm	553 nm	544 nm	538-541 nm

The spectral response peak of the left, center, and right HPW vs. angle of incidence and field-of-view angles are shown (Figures 34 and 35). These curves have some discontinuity points associated with variations produced by cosmetic defects. The lack of symmetry of some of these curves with respect to the 0° values is also associated with cosmetic defects which are more predominate in one direction. The cause of this asymmetry was that the holographic mirror centers were displaced from the center of the HPWs and the cosmetic defects increased with the distance from the center. The right and left side HSBM were constructed with their center 0.5" from the center of the plate in agreement with the design of the HPW mosaic. During the HPW's assembly the HSBM were interchanged to obtain a better match of other parameters. Consequently, the right side HSBM used in the left side HPW has a $0.5" \times 2 = 1"$ center displacement and vice versa.

The transmission of these left, center, and right HPWs was measured with various sources. Because of the relatively narrow bandwidth of these HPWs (20nm to 25nm half-width) the transmission efficiency depends on the spectral match of the illuminating source. Maximum efficiency will occur with sources having a spectral bandwidth narrower or equal to the spectral distribution of the HPWs. The spectral distribution of the P-31 phosphor was simulated with a filter with approximately 100nm half-height bandwidth. The average transmission values are plotted in Table 4.

The ghost images in these HPWs are qualitatively the same as in the classical Pancake Window. The stronger ghost is the direct view of the information displayed in the CRTs; this ghost designated is the bleed-through or reject image. The multiple reflections between the beamsplitter are called R_2 , R_3 , R_4 , etc. ghost images and are real images formed between the Pancake Window and observer. Because of the very low brightness of these real images, they do not usually affect the performance of the Pancake Window.

The bleed-through ghost in the HPW is also affected by the match of the spectral illumination distribution and the HPW spectral response. The illumination light falling outside the spectral response of the HPW is not used in the wanted image but still is going through the HPW and contributing to the bleed-through. Values of the bleed-through for various sources are shown in Table 5 for the left, center, and right HPWs.

The resolution is not uniform throughout the entire

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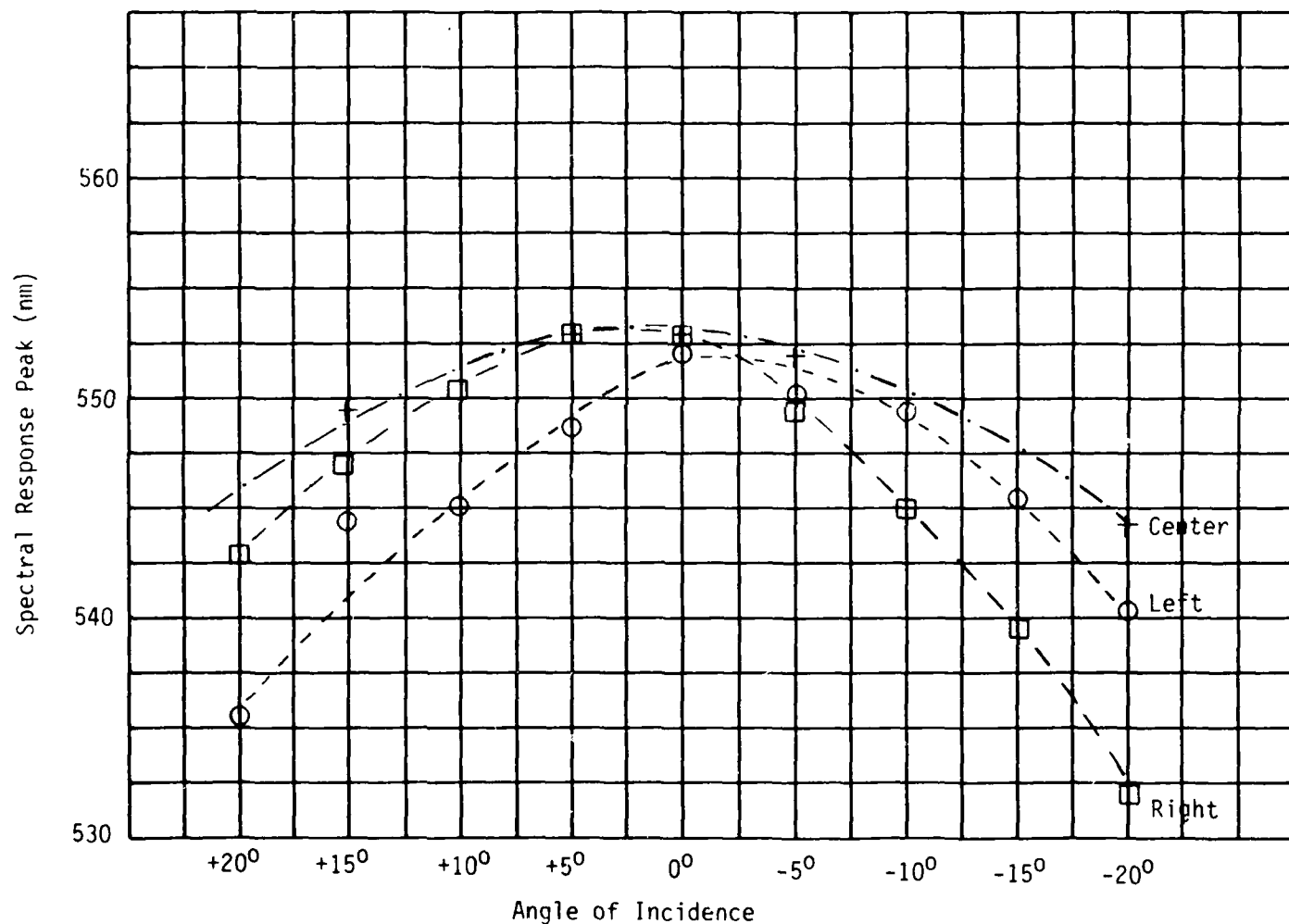
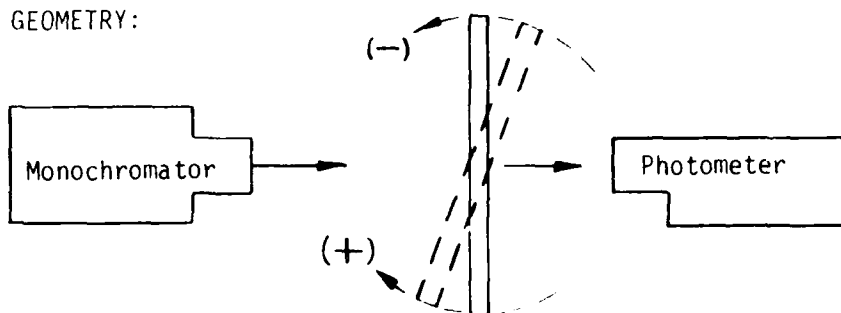


FIGURE 34 SHIFT OF SPECTRAL RESPONSE PEAK VS. ANGLE OF INCIDENCE FOR THE CENTER, RIGHT, AND LEFT HOLOGRAPHIC PANCAKE WINDOWS IN THE MOSAIC CONFIGURATION

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FARRAND OPTICAL CO INC VALHALLA NY
LOW COST, WIDE ANGLE INFINITY OPTICS VISUAL SYSTEM.(U)
SEP 81 J R MAGARINOS, D J COLEMAN

F/G 14/5

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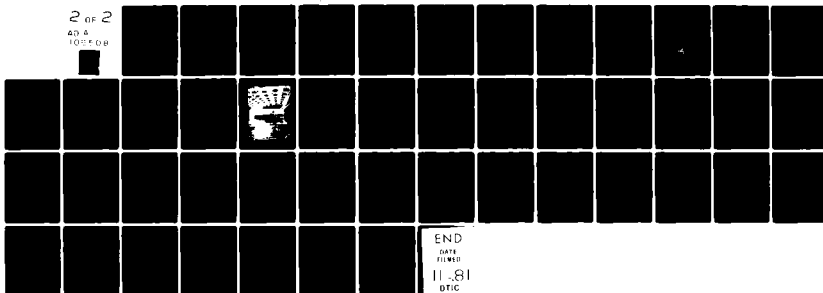
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GEOMETRY:

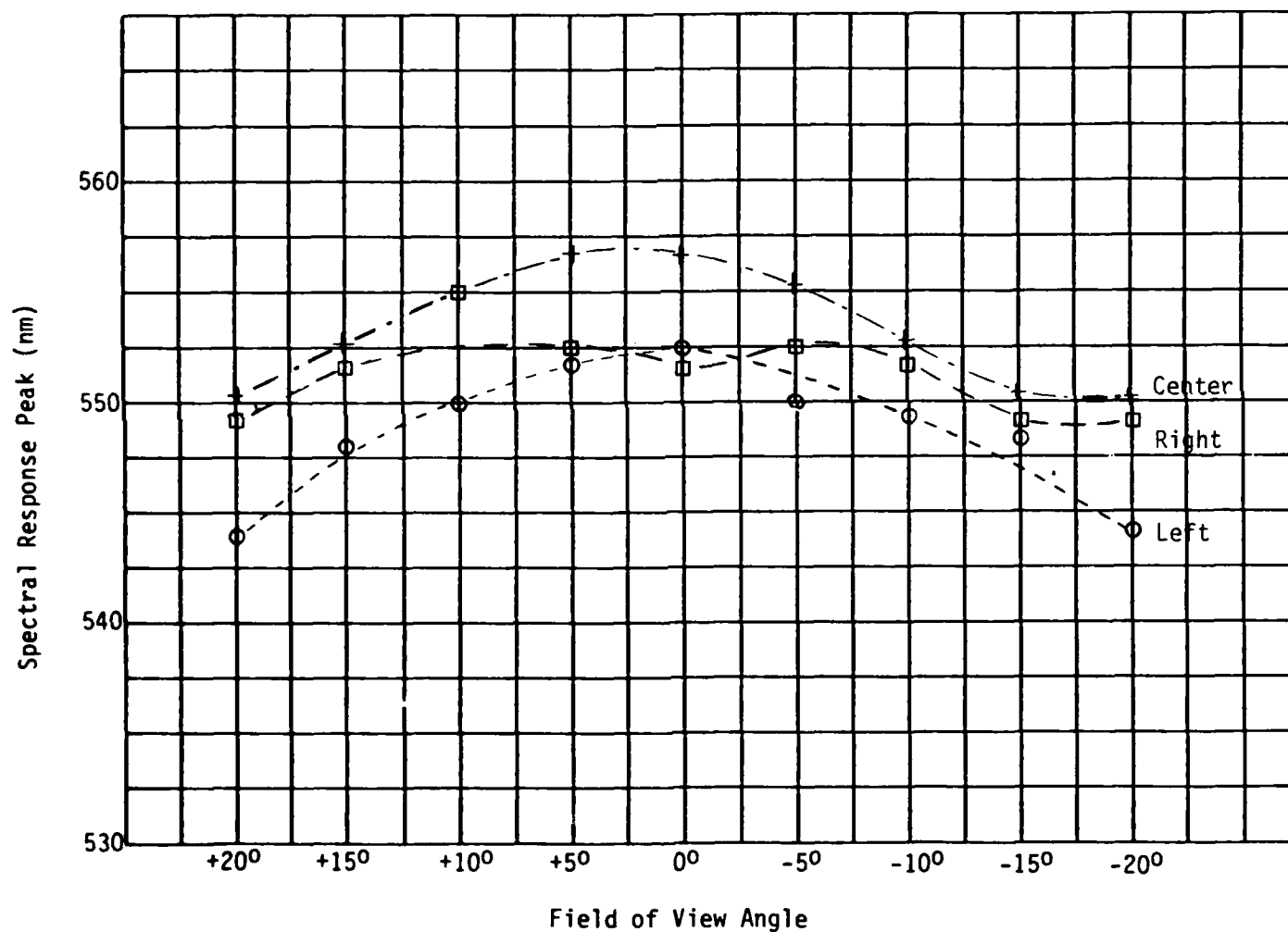
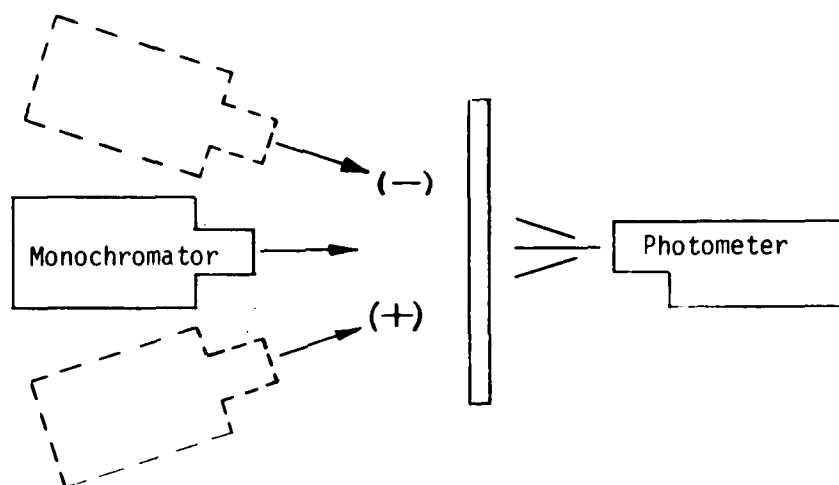


FIGURE 35 SHIFT OF SPECTRAL RESPONSE PEAK VS. FIELD-OF-VIEW ANGLE FOR THE CENTER, RIGHT, AND LEFT HOLOGRAPHIC PANCAKE WINDOWS IN THE MOSAIC CONFIGURATION

TABLE 4

HOLOGRAPHIC PANCAKE WINDOWSTM
TRANSMISSION FOR VARIOUS SOURCES

SOURCE	LEFT HPW	CENTER HPW	RIGHT HPW
Monochromatic	0.89%	0.82%	0.89%
Fluorescent Day Light	0.31%	0.23%	0.3 %
Same Fluorescent Plus Filter	0.45%	0.3 %	0.4 %

TABLE 5

BLEED-THROUGH TRANSMISSION
AS PERCENT OF VARIOUS SOURCES

SOURCE	LEFT	CENTER	RIGHT
	HPW	HPW	HPW
Monochromatic	0.02	0.011	0.011
Fluorescent	0.066	0.038	0.03
Fluorescent Plus Filter	0.05	0.034	0.029

field-of-view and the worst resolutions are associated with cosmetic defect areas in the holograms. For various positions in the pupil, the best values of the resolution at the center of the field-of-view of each window is 0.89 minute of arc and the worst is 10 minutes of arc. The resolution is not as good, in general, throughout the entire field-of-view, and areas with resolution as bad as 25 minutes of arc could be found. On the other hand, it is also possible to find selected areas with a resolution of 0.89 minute of arc in the field-of-view, including the most extreme angles.

Experimental HPW to be Used with a P-44 Phosphor

As mentioned in Section VI, a HSBM can be designed so that when it is used in the Pancake Window configuration with a P-44 narrow phosphor, the variations of transmission vs. field-of-view angles are minimized. A hologram was produced which was close enough to the ideal design to demonstrate experimentally this solution. Subsequently, a HPW was assembled with oil (not with optical cement) and evaluated. The diffraction efficiency of this HSBM is plotted in Figure 22 for angles of incidence of 0° and $+25^\circ$ as a function of wavelength. It should be noted that the diffraction efficiency is not required to be lower than 50% (the narrow spectral distribution of the P-44 phosphor prevents a double peak spectral transmission). It should also be noted that the 0° distribution and the $+25^\circ$ distribution are not symmetrical (as, ideally, they should be) to the P-44 phosphor. The variation in transmission across the field-of-view ($+20^\circ$) was quite small and should be even smaller for a 0° peak and $+20^\circ$ peak which is totally symmetrical with respect to the P-44 phosphor peak (Figure 36). The advantage of this solution, which has been proven experimentally, is the higher efficiency of the HPW-CRT system. The average 0.4% transmission using the P-31 phosphor will be increased to 1% transmission using the P-44 phosphor.

GEOMETRY:

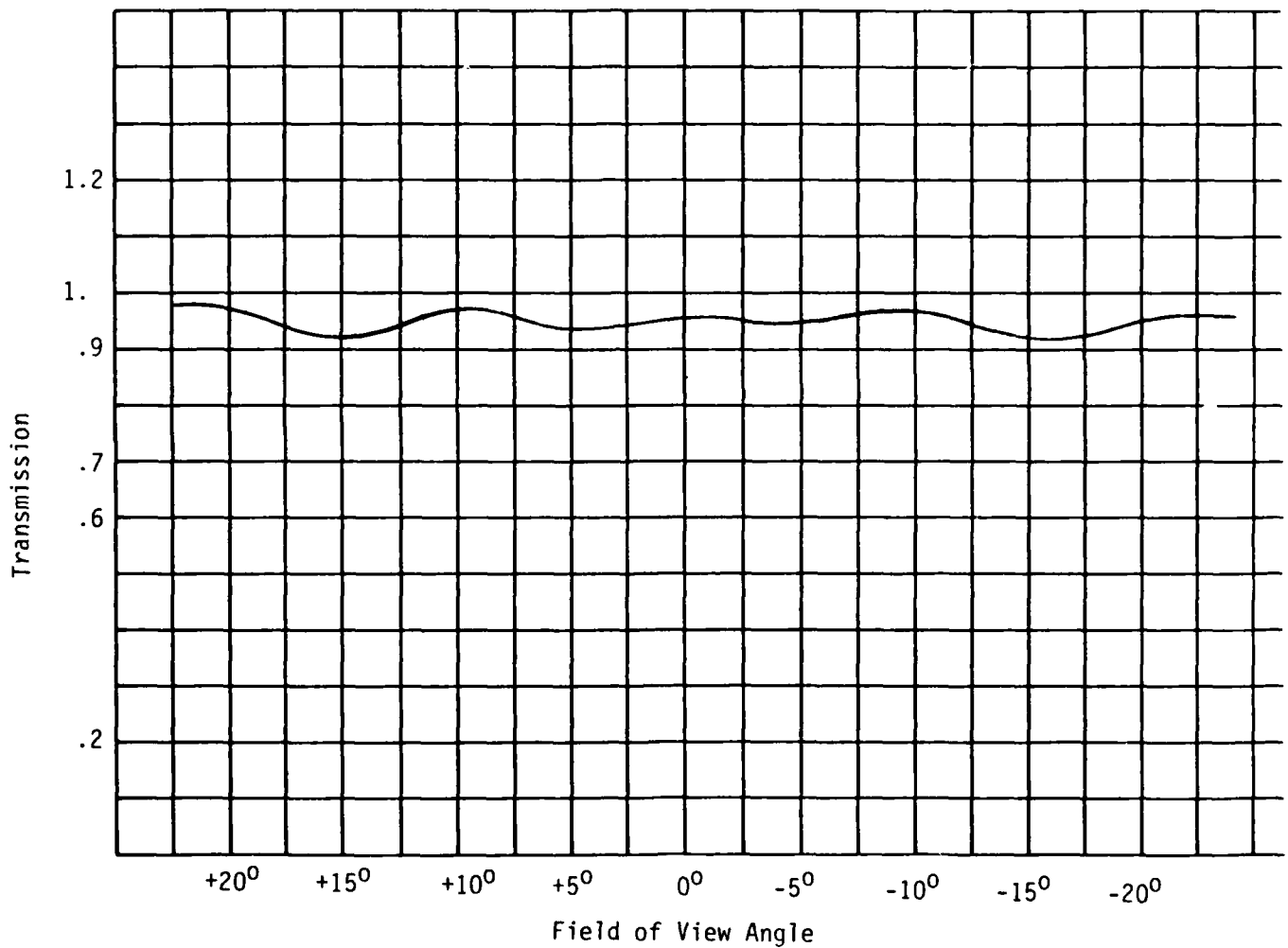
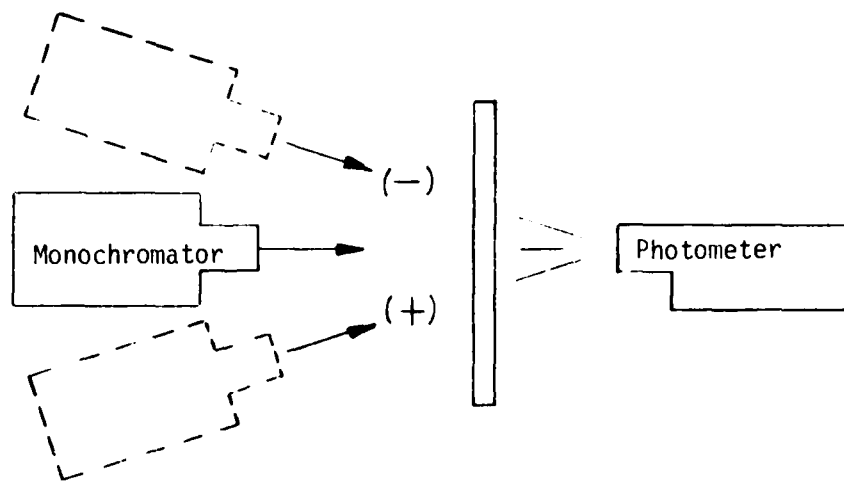


FIGURE 36 TRANSMISSION VS. FIELD-OF-VIEW ANGLES OF EXPERIMENTAL PANCAKE WINDOW WITH A HOLOGRAPHIC SPHERICAL BEAM-SPLITTER AND P-44 PHOSPHOR ILLUMINATION

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

ABOUT THE HOLOGRAPHIC PANCAKE WINDOWS

Conclusions

Two fundamental problems were encountered during manufacture of the HSBM mirrors that were to be used in the holographic mono-color Pancake Windows. One was the interferometric instability of the first designed vertical wet cell. This instability caused the holograms to have dark black bands throughout the holographic plate surface, with the consequent loss of signal strength and signal uniformity. This problem was corrected, after many unsuccessful modifications of the vertical wet cell, with a horizontal wet cell. The horizontal wet cell required a very thick (1" thick) base plate support, but avoided hydrostatic pressures and glass sagging believed to be the cause of a very small but continuous movement of the holographic plate during the time of exposure.

The second fundamental problem was a shift of the hologram wavelength response after development and also with off-axis incidence angles. This problem became very severe when the hologram (assembled in the HPW configuration) was illuminated with a narrow band phosphor, P-44. The shift of the holographic wavelength response away from the center of the phosphor emission distribution produced a loss of transmission, and the shift with respect to angles of incidence or field-of-view angles produced a severe darkening at the edges of the window (extreme field-of-view angles).

Two solutions for this problem were proposed. The easiest one (not necessarily the best) was implemented with the purchase of new broad-band phosphors (P-31) for the CRTs. These phosphors, being more than three times wider than the hologram response, produced a uniform transmission and a uniform field-of-view illumination even for the largest shifting of the hologram wavelength

response. The broad band phosphors were, on the other hand, much less efficient in producing a useful illumination and only about a one-third of the phosphor distribution emission was used by the holograms. The transmission of the windows, although uniform, was one-third of that achievable with the narrow P-44 phosphor.

These two problems have been the most fundamental and most directly related to this program. At the beginning of this program, other fundamental problems from the previous program involving the 17" holographic window were studied and resolved. The first problem involved new holographic ghosts caused by multiple hologram registration but this problem was eliminated with the use of a wet cell. Second, the loss of contrast and resolution were caused by a double wavelength distribution transmission of the HPW and resulted from the use of holograms with a diffraction efficiency higher than 50%. The problem was resolved either by using a very narrow illumination source (such as the P-44 phosphor) or by keeping the diffraction efficiency below the 50% value. The third problem was lack of holographic response uniformity, repeatability, and cosmetic defects caused by poor holographic facilities and poor control of environmental parameters, particularly temperature, humidity, and cleanliness. To correct these problems, new holographic facilities were designed and built. With these controls it was possible to establish the best and most important parameters in the production of very flat holographic film with the correct hardness and, in general, the parameters to maximize and control the entire holographic process.

The schedule of this program was severely affected and delayed by the dark band instability problem and as a consequence of it, the quality of the final delivered product was tempered by financial and schedule constraints. The implementation of a broad band instead of a narrow band phosphor facilitated the production of the three holograms providing very large tolerance in wavelength response or wavelength shifting but penalizing (by two-thirds) the transmission of the HPWs. The fastest approach in finalizing the program prevented the implementation of the established (but more time consuming) techniques to achieve perfectly flat and uniform films and elimination of cosmetic defects. It was argued that the perfection of the HPW was not fundamental to evaluating the feasibility and general performance of the three HPWs in a mosaic dynamic display configuration

Recommendations

It is recommended that once the feasibility and acceptable performance have been demonstrated, the system be upgraded to maximize the performance of each HPW. Specifically, with present technology, the following can be improved considerably: (a) the uniformity of the holograms and elimination of cosmetic defects, (b) the resolution throughout the entire field-of-view, (c) the transmission of the HPWs. The HPW transmission can be improved by a factor of about three by designing and manufacturing the holograms specifically for use with the P-44 phosphors. This approach has been experimentally proven and is described in Section VII of this report.

SECTION IX
SYSTEM DESCRIPTION

General Description

The purpose of the Wide-Angle Low-Cost Infinity Optics Visual System (WALC) is to demonstrate advanced training simulation and to evaluate the technical, feasibility, and performance qualities of an integrated system under static and dynamic operating conditions.

The basic system (Figure 37) consists of the following items:

1. A three-dimensional, color terrain model and support structure with a scale factor of 2000 to 1. The model provides general terrain information and airport landing information as well as general airport lighting and city-type lighting.
2. An illumination subsystem composed of an array of metal haloid lamps which provide the required illumination for the terrain model.
3. A gantry assembly which supports a probe and video pickup (with its associated electronics) and has the capability to translate these mechanisms in X, Y, and Z directions.
4. A wide-angle optical probe which provides the three degrees of rotational freedom (i.e., roll, pitch, and heading) and in addition maintains the near and far fields of the terrain scene in optimum focus.
5. A T.V. camera pick-up system which relays the output of the probe to the processing electronics from which it is directed to the three projection CRTs.
6. Three CRTs with their associated electronics which provide the source of the image to the windows.

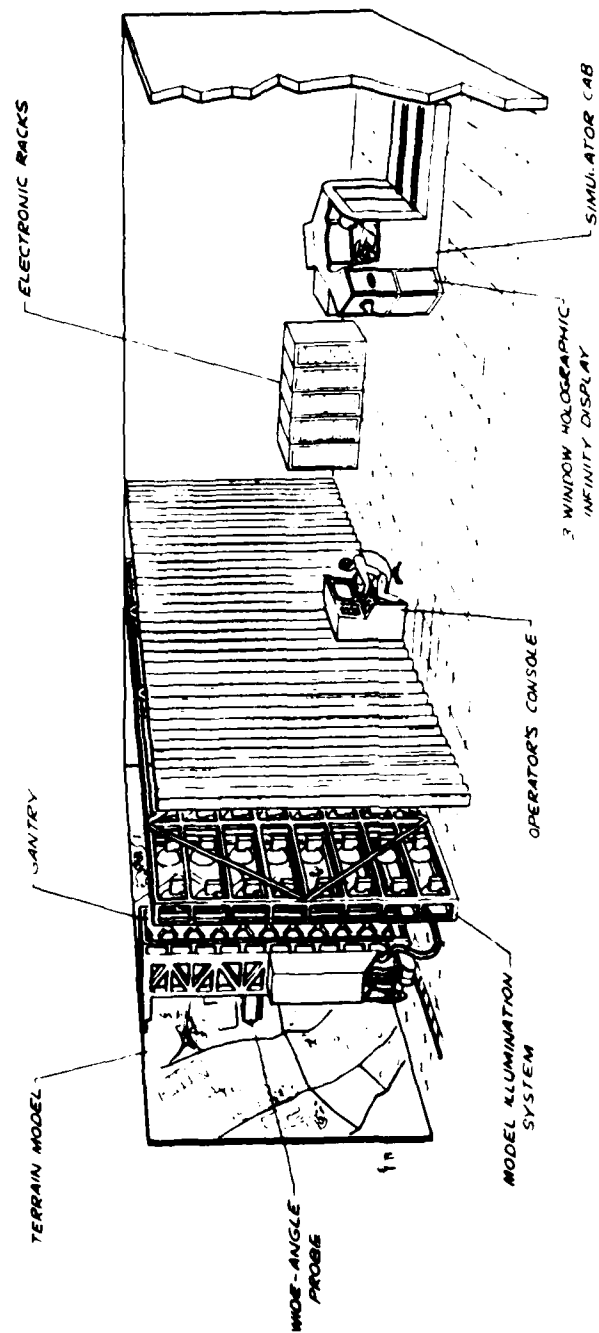


FIGURE 37. WIDE-ANGLE LOW-COST INFINITY OPTICS VISUAL SYSTEM

7. A display consisting of an optical mosaic of three HPWs.

The entire system is interconnected as shown in the block diagram of Figure 38.

As another feature, an Instructor/Maintenance Panel is provided which enables an instructor to manually operate the system without the computer. At this station, a T.V. monitor, all servo controls, and auto/manual mode switching logic are incorporated. Normally the system is under complete computer control of the Simulation and Training Advanced Research System (STARS) facility.

Detailed Description

Terrain Model. The model is constructed on aluminum honeycomb panels. The panels are stiff and strong enough to be handled and shipped without damage. The construction is much more durable than fiberglass systems, although considerably more expensive to construct. The seams are close fit and blended in the field by adding flock and tree line continuity across them. The structure is bolted together, panel by panel, and stabilized from the floor and one wall. A structure fastened to the building wall supports the top rail for the X, Y gantry as well as the top support for the model. A scaffold is located behind part of the model to allow access to the airport lighting system for maintenance.

The model is 28 x 40 feet. The maximum panel width is 84". The length varies between 10 and 16 feet and the airport section is a separate unit. To give good runway light alignment and realism, the runway plate is jig-bored.

The landscape represented is symbolic of a typical commercial airport with three major runways, taxi-ways, hangar, and terminal facilities. The general terrain is gently rolling, grassy, and tree intense with rivers and small lakes interspersed throughout. A moderate size town, surrounded with farmland, is located on one side of the model. Color is rendered in greens, browns, and tans. The water areas are carefully painted to give slight semi-spectral reflections to appear wet when viewed at low angles by the probe/camera. The general base texture is a fine flocked material; the trees and other representations are carefully painted to prevent specular reflections.

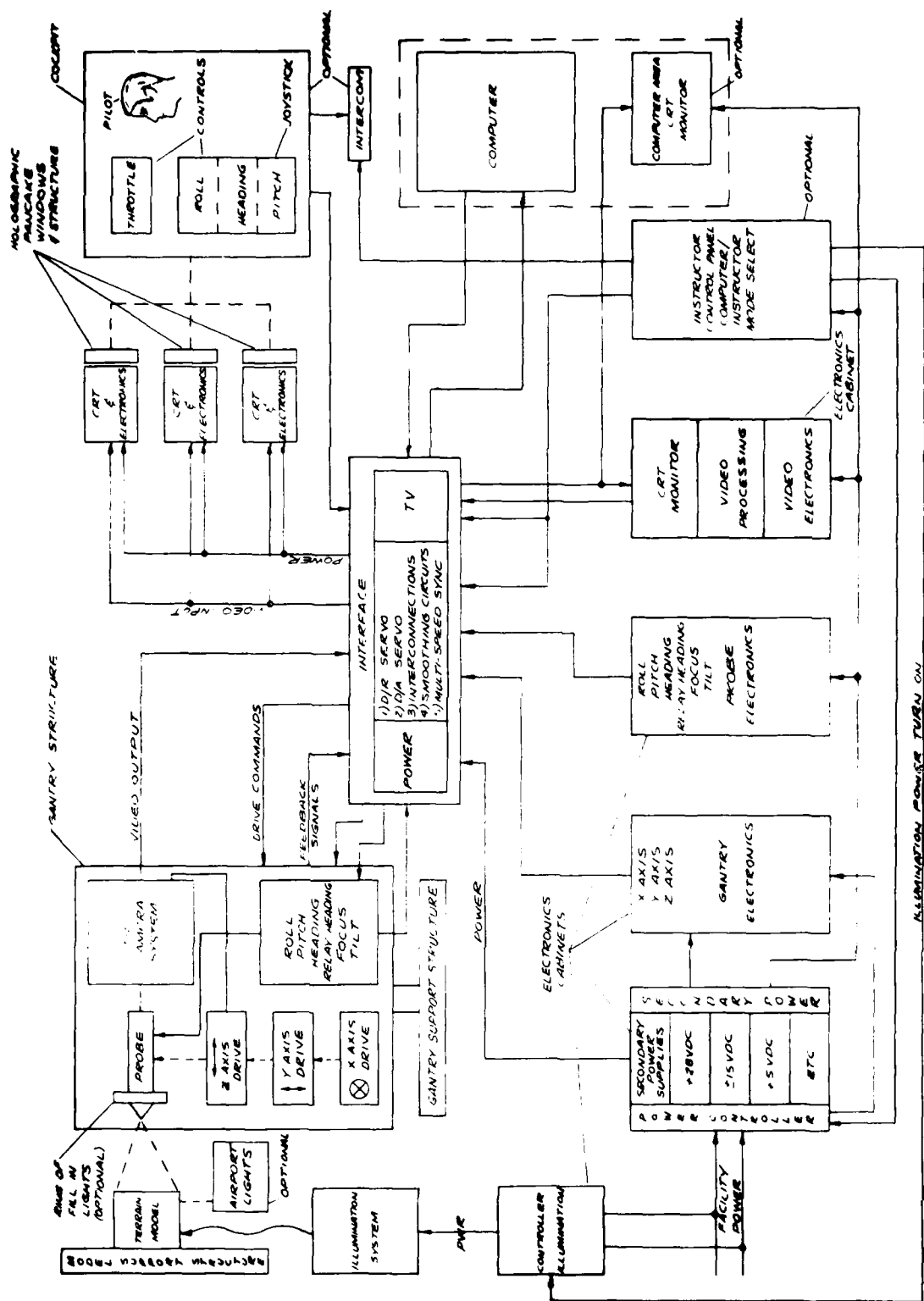


FIGURE 38. SYSTEM BLOCK DIAGRAM, WIDE-ANGLE LOW-COST INFINITY OPTICS VISUAL SYSTEM

Night lighting is extensive with complete airport runway, approach lights, animated strobe lights, wing bars, narrow gauge and centerline lights, high speed turn-off lights, as well as taxi lights. The tower, buildings, and beacons are lighted. The town and surrounding houses as well as some major streets are also lighted. All of the lights are controllable in intensity. Runway and other lighting systems switching is incorporated. The lights are generated by small fiber optic light pipes. The fiber optic light pipes for the approach and runway lights are ground to represent directivity at low angles similar to the real world.

Illumination. The master lighting is provided by 88 1000-watt Metal Halide lamps giving approximately 2800 foot lamberts of model board illumination. Each lamp fixture has its own ballast transformer. The parabolic reflectors are selected to transfer maximum energy to the model board. They are focused to minimize shadows and provide good uniformity.

The light banks can be switched in interspersed arrays to give dusk lighting effects. The lights are mounted on open scaffolding. Individual fuses as well as master circuit breakers are provided. The wiring is all conduit enclosed.

Total lamp power required is 105 KVA. The lamps and reflectors are removable.

Gantry. The gantry is a steel weldment 28 feet high by 40 feet by 3 feet and is designed to be very stiff. The system has a narrow aspect ratio to allow the probe to approach the room walls as closely as possible. The gantry, including the probe/camera system, weighs approximately 8,000 pounds.

The gantry structure provides X, Y, and Z motion to the camera via servo-drive mechanisms. X motion is along the length of the vertically mounted model. A horizontal floor rail precisely positioned with respect to the model establishes the X-axis. An upper guide rail, precisely aligned to the model and lower rail, establishes the attitude of the X-Y motion plane. Within the gantry vertically aligned columns maintain true (Y) motion for the camera platform. This platform also contains the Z servo drive, which provides altitude motion to the camera. The X servo is designed to be used either as a position or velocity servo; however, under computer control, only the velocity mode is used.

The follow-up coarse signal potentiometer used in the local position mode and the fine signal sine/cosine potentiometer used in the velocity mode are both infinite resolution types. They are rigidly mounted to the gantry and are driven through anti-backlash gearing by a precision gear rack which is mounted on the floor and extends the length of the model. A precision DC tachometer is attached directly to the motor shaft and provides the entire feedback signal for velocity mode and a damping signal for position mode.

The sine/cosine feedback element is used to provide high resolution positional information to the computer interface, where it may be employed to close the loop through the computer. The loop itself is a Type 2 servo which theoretically provides zero positioning and velocity error. A chopper-stabilized amplifier is used for error summing to guard against drift.

The Y servo is quite similar to the X servo, differing primarily in the drive arrangement. The physical make-up of the system allows a counterweight to be employed in Y, and this, with the inherently smaller load, allows a 22 foot-lb. motor to be used. The friction drive of the X motor is replaced by a helical friction drive which provides both zero backlash and mechanical damping.

The Z servo also employs a helical friction drive arrangement and utilizes a direct drive DC torque motor. Only a single position follow-up is required, due to the limited travel required in altitude. This is provided by an infinite resolution, .05% linearity potentiometer. As in X and Y, tachometer signals are provided for optimizing loop performance.

An extensive logic arrangement is incorporated into the system to protect against equipment failure and pilot error. A FAIL line is established where automatic monitoring is provided on such critical components as power amplifier and power supplies, while a CRASH line monitors pilot maneuvers. Hard stops on all three axes limit maximum excursions to safe limits. Dangerous-rate sensors, both absolute and as a function of aircraft position, are employed. An envelope of varying allowable minimum altitudes over mountainous terrain, normal terrain, and airport complex is created through cam-controlled switches actuated in response to X, Y, and Z position.

On the ground (at the airport) where taxi motion

cannot easily be restricted, buildings that might be struck by improper taxiing are free to move a certain distance, this movement actuating a crash condition, which automatically stops all X and Y motion and causes Z to retract. A manual crash reset command is required by the instructor to re-enable the system.

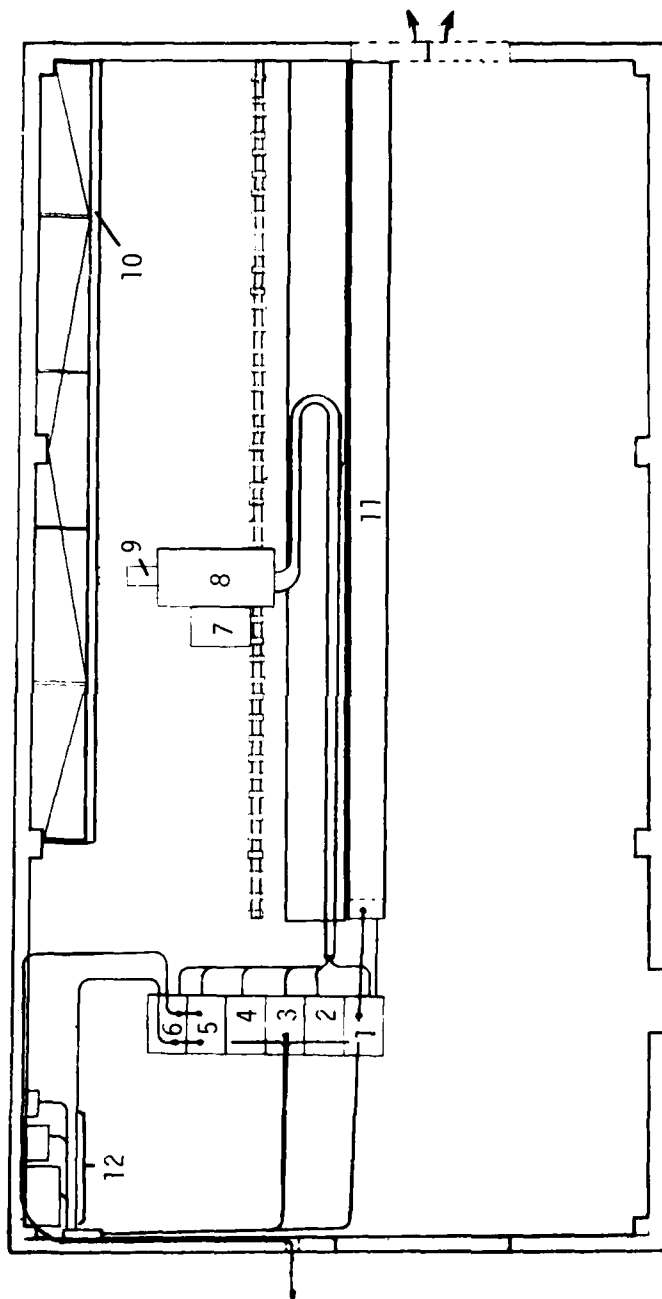
Figure 39 (Facility WALC Display System) shows the configuration and location of the terrain model, gantry, and illumination system as installed on site at Wright-Patterson Air Force Base (WPAFB). A more detailed view of the gantry-model system is shown in the photograph of Figure 40.

Optical Probe/Camera Assembly. Figure 41 shows the layout of the optical probe and T.V. camera assembly. The system is composed of three major components:

1. Optical scanning probe.
2. Field splitting and relay optics.
3. Three T.V. cameras.

In operation, the 140° field-of-view of the optical scanning probe is split into three equal circular fields of approximately 68° . These are then relayed to the face of the camera tubes such that each camera "sees" a field-of-view of 50° horizontally by 45° vertically, with a 5° overlap between field. The total field as seen by the three cameras is then 140° horizontal by 45° vertical.

Optical Scanning Probe. The optical scanning probe that forms part of the probe/camera assembly is a refurbished and completely mechanized version of an engineering feasibility model wide angle probe provided as Government furnished equipment. Since this contractor has built servo-driven versions of the 140° WPAFB probe employing identical optics, the method of approach was to strip the hand-driven probe and retain all parts identical to the ones used in the servo-driven model. The refurbished probe contains three main gimbal axes: pitch, heading, and roll. Three additional axes (tilt, relay heading, and focus) respond to altitude and heading altitude and thereby maintain the near and far fields of the terrain scene in focus. The servos for the probe are high accuracy positional systems which utilize multispeed transducers and therefore accept absolute position information from the computer rather than velocity information as does the gantry. The servo drives for the



LEGEND

- 1 - 6 Gantry Controls
- 7 Probe & Camera Controls
- 8 Gantry
- 9 Probe & Cameras
- 10 Model Board
- 11 Light Bank
- 12 Power Converters

FIGURE 39. FACILITY WIDE-ANGLE LOW-COST
DISPLAY SYSTEM

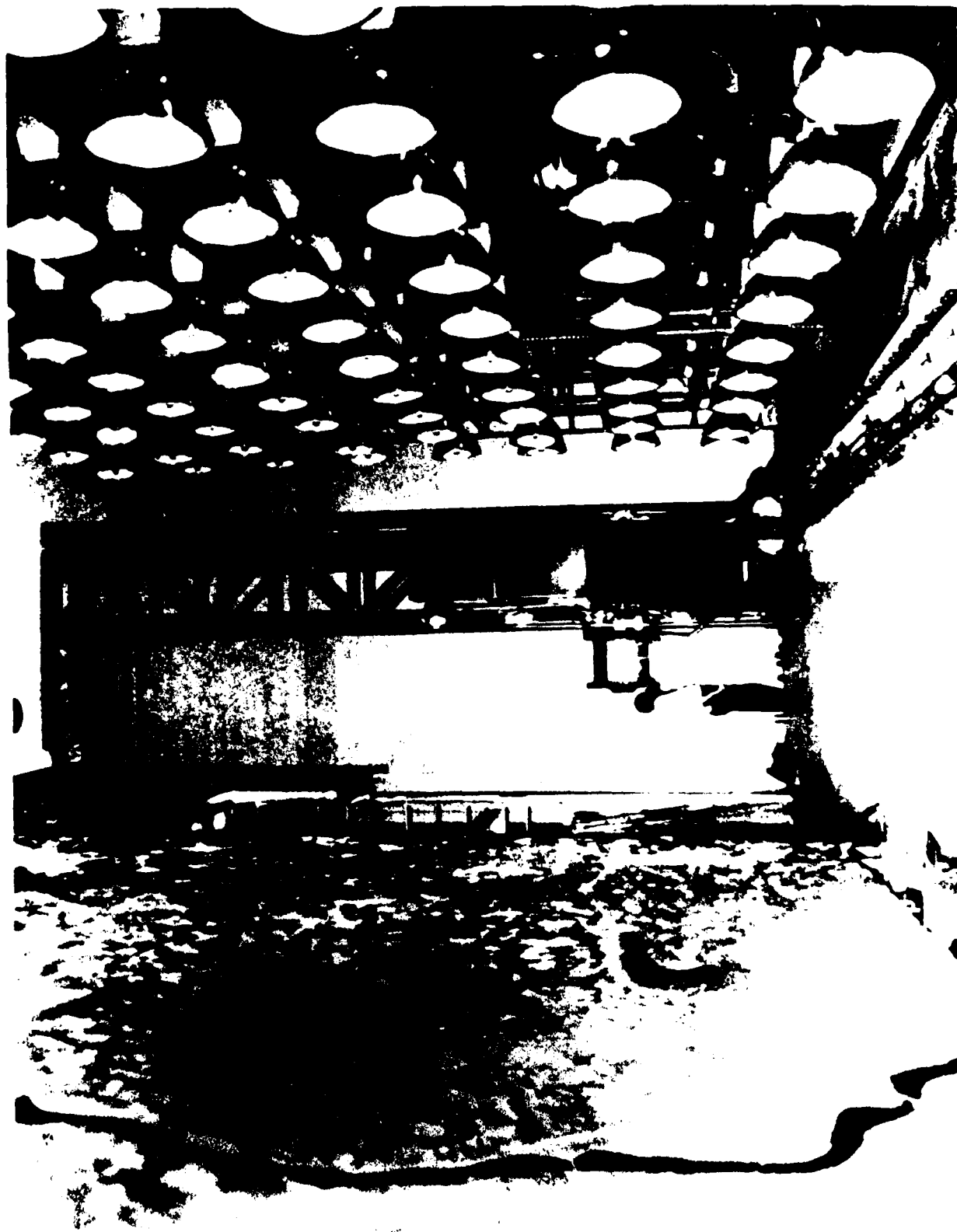


FIGURE 40 MODEL-GANTRY SYSTEM

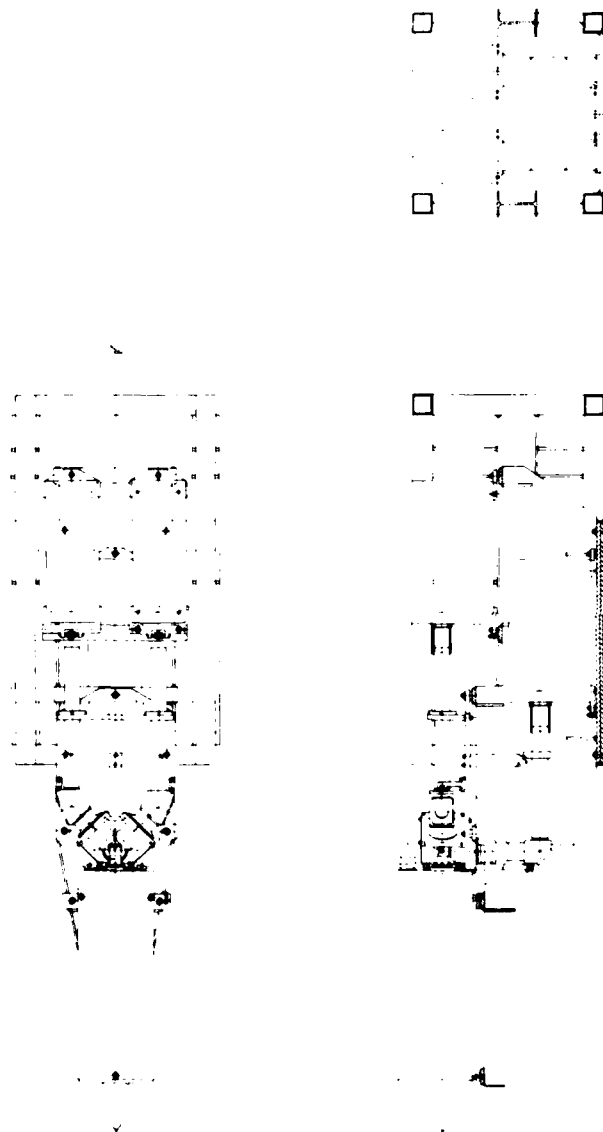


FIGURE 41.
FINAL ASSEMBLY (PROBE-CAMERA INTERFACE)

axes are independent of each other. Each servo responds to four-wire, 400-Hz resolver input signals except for tilt and focus. These latter two, which use linear feedback potentiometers, respond to D.C. signals within the range of $\pm 10V$. The focus, tilt, and pitch drives, each being limited motion mechanisms, are protected both by electrical limit switches and mechanical stops. Heading, roll, and relay heading are continuous in rotation and required no such protection.

Since the resolver feedback elements are geared to the line of sight by a factor of 4 (i.e., one turn of the line of sight = four turns of the resolver), a simple switch closure is used to identify one of the four possible quadrants of the line of sight. Signal and power to the probe are transmitted by means of three cables into three connectors, J1, J2, and J3 located at the rear of the probe. The control and drive electronics for the probe are housed in two standard 19-inch rack-mountable chassis and are located within a cabinet fastened to the gantry.

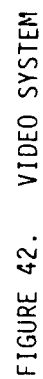
Closed Circuit T.V. System. The closed circuit T.V. system used in the WALC is shown in Figure 42. It is composed of two main parts, the video image generation system and the 25-inch CRT display system.

The video image generation system is made up of the following components:

1. Three camera heads
2. Camera control unit
3. Camera control unit power supply
4. Special effects generator
5. Remote raster correction unit

The cameras are identical units. Each one contains its own horizontal and vertical deflection amplifiers, blanking and sweep protection, a video preamplifier, and the camera tube.

The camera control unit, located in a separate chassis on the gantry, provides the necessary signals for the camera heads and also processes the returning video.



Located within the camera control unit are the master sync generator, horizontal and vertical sweep generators for the cameras, camera sweep correction modules, camera high voltage power supply, and video processing modules for the three cameras.

All camera power requirements are generated in the camera power supply chassis and relayed to the individual cameras via the camera control unit.

The special effects generator accents the signals from the camera control unit and, by special electronic techniques, adds synthetic ceiling control, visibility control, closed top control, day, dusk and dark control and cultural light enhancement. The resulting signals, in the form of horizontal and vertical drives, composite blanking, and the left, center, and right channel video, are sent via video line drivers to the cathode ray tube display system, located approximately 300 feet away.

The remaining part of the image system is the remote raster correction unit. This unit, which operates on the correction modules referred to in the camera control unit, makes available the following corrections to each of the camera rasters:

1. Size
2. Position
3. Linearity
4. Linearity Offset
5. Pincushion/Barrel
6. Pincushion/Barrel Offset
7. Curvature
8. Curvature Offset
9. Keystone
10. Orthogonality
11. "S" Correction

Each control has its own separate on/off switch so that each correction can be enabled in sequence to obtain an approximate correction. Then, with all controls on, the final correction adjustments can be made. Corrections which are not needed can be eliminated in the final result by merely turning off the appropriate coefficient switches. Knob locks are provided so that controls are not inadvertently moved.

The 25" CPT system is a high resolution, high brightness display system consisting of three identical sets of drive electronics and a common remote control panel. Each

display is designed to have a 30MHz video bandwidth, electronic circuitry to minimize geometric distortion and deflection defocusing, and stabilization techniques to provide an accurate repeatable display with minimum drift. The display unit also incorporates protection circuitry to protect the CRT during turn-on, turn-off, or in the event of sweep failure.

The display is capable of being driven by standard transistor-transistor-logic (TTL) drive signals and non-composite 1 volt peak to peak white-up video to provide a 1023 line, 2:1 interlace 60 fields/second display. Each display consists of a power supply chassis, deflection amplifier chassis, yoke, focus coil, video amplifier, high voltage power supply, and high brightness CRT.

As can be seen from Figure 42, the drive signals are received and buffered by the line receiver, located in the video signal interface. The horizontal drive pulse is delayed and shortened to compensate for delays in the horizontal amplifier and, with the vertical drive pulse, is applied to the sweep generator located within the deflection amplifier chassis. The blanking pulse is routed through the sweep failure board directly to the video amplifier.

The horizontal and vertical sweeps are generated from the drive pulses. In each case, reference voltages from the size control are integrated until the drive pulse resets the integrator. The ramp is then summed with a portion of the reference and the position control voltage to provide centering. Both sweeps are negative sloping ramps and are approximately $\pm 10V$ in amplitude when the size is adjusted for maximum.

The horizontal and vertical linear sweeps are modified by correction circuits to correct for geometry distortion. Squared and cubic waveforms of each sweep are generated and summed with the linear sweep. The dynamic focus waveforms are also developed by the correction circuits. The output sweeps are approximately $\pm 10V$ in amplitude at maximum size.

The corrected horizontal sweep is connected to a voltage controlled current sink with a transfer function of approximately $1.4A/V$. The current from the constant current source flows through the horizontal deflection coil and/or the output transistors as a function of the input voltage and polarity. Sweep amplitude is nominally 17 A peak to peak. The horizontal amplifier is protected by a thermistor circuit which forces the current sink in the

off direction if the temperature exceeds approximately 190°F.

The corrected vertical sweep is amplified by a voltage-to-current converter with a transfer function of approximately 0.9 A/V. Sweep amplitude is nominally 12 A peak to peak.

The CRT is protected by circuitry which samples the sweeps, and in the event of a failure, the CRT is blanked and the high voltage supply turned off.

Dynamic as well as static focus waveforms are also developed within this deflection amplifier.

The video is connected directly to the video amplifier located at the display. The amplifier gain is variable from 0 to approximately 40 (at the cathode) by the contrast control. Damage due to arcs is minimized by spark-gaps and neons across the outputs.

The anode voltage is generated by the high voltage power supply by developing approximately an 800 V pulse at the horizontal rate, multiplying the voltage and rectifying. The output is adjustable between 1 and 30 V and is normally adjusted for 25 V by a trimmer located on the PC board. A sample output is provided for monitoring the anode potential.

Figure 43 shows the actual display system configuration. The three displays are mounted on a table, in the orientation shown. Next to each CRT is a high voltage power supply (20 P51 - 20 P53) and a video amplifier (20 V1AR1 - 20 V1AR3) mounted directly to the yoke assembly. Deflection amplifiers and deflection amplifier power supplies are located in UNIT #7 while the line receiver chassis is located within UNIT #9.

The high brightness CRT's are 25" rectangular, all glass magnetic deflection, and electromagnetic focus tubes. These tubes are rated at 500 foot Lamberts brightness at the sweep speeds and refresh rates of the system. The phosphor is a special green, peaking at 540nm with a bandwidth of approximately 100nm. This peak was chosen to match the peak response of the three holographic windows.

Holographic Pancake Window. Figure 44 shows the layout of the three-window display system designed to provide a minimum instantaneous field of 45° vertically by 140° horizontally using the HPW of 32" diameter. Note that these restraints automatically determine the eye relief distance in this case approximately 26".

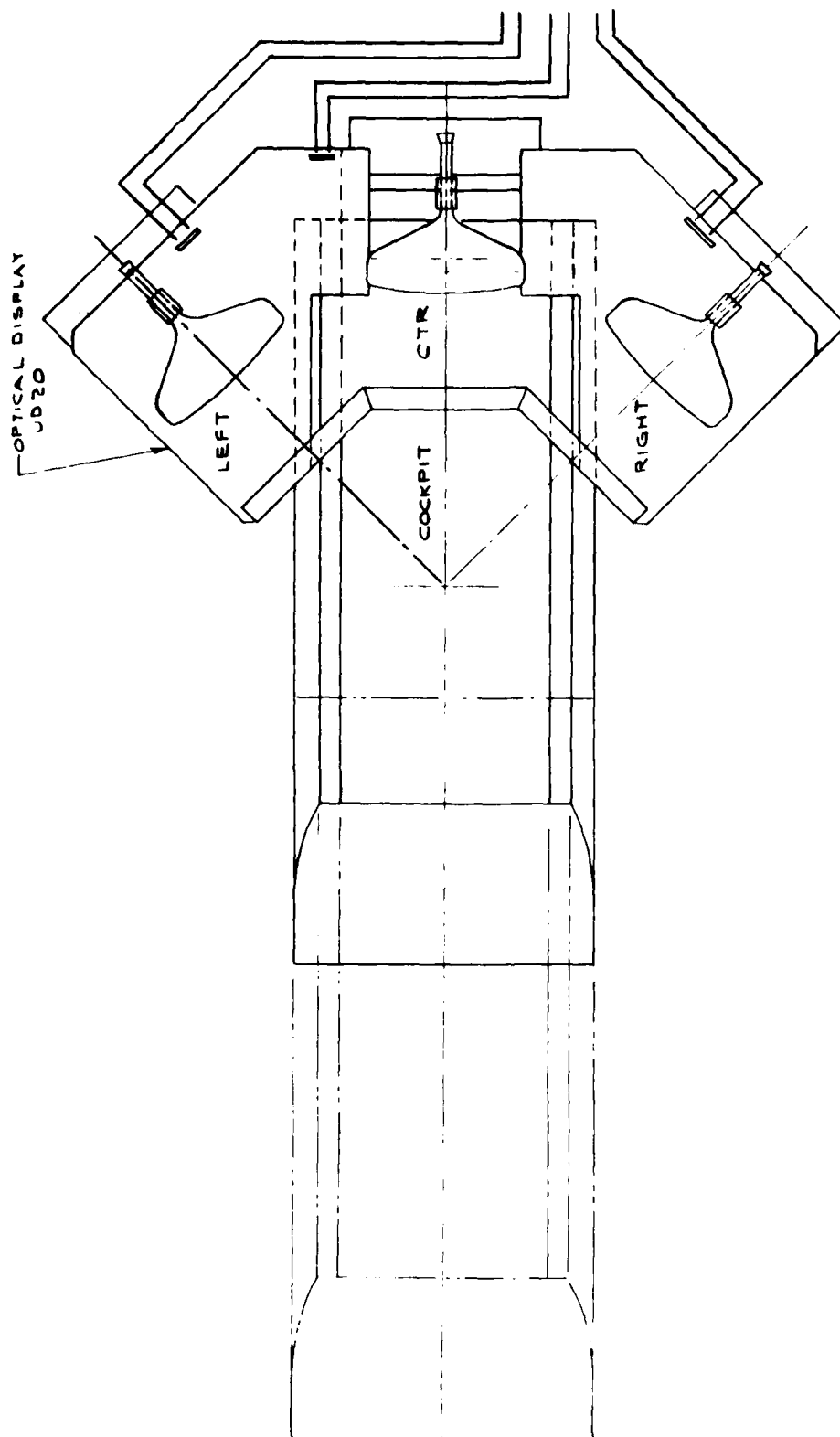


FIGURE 43. VISUAL DISPLAY

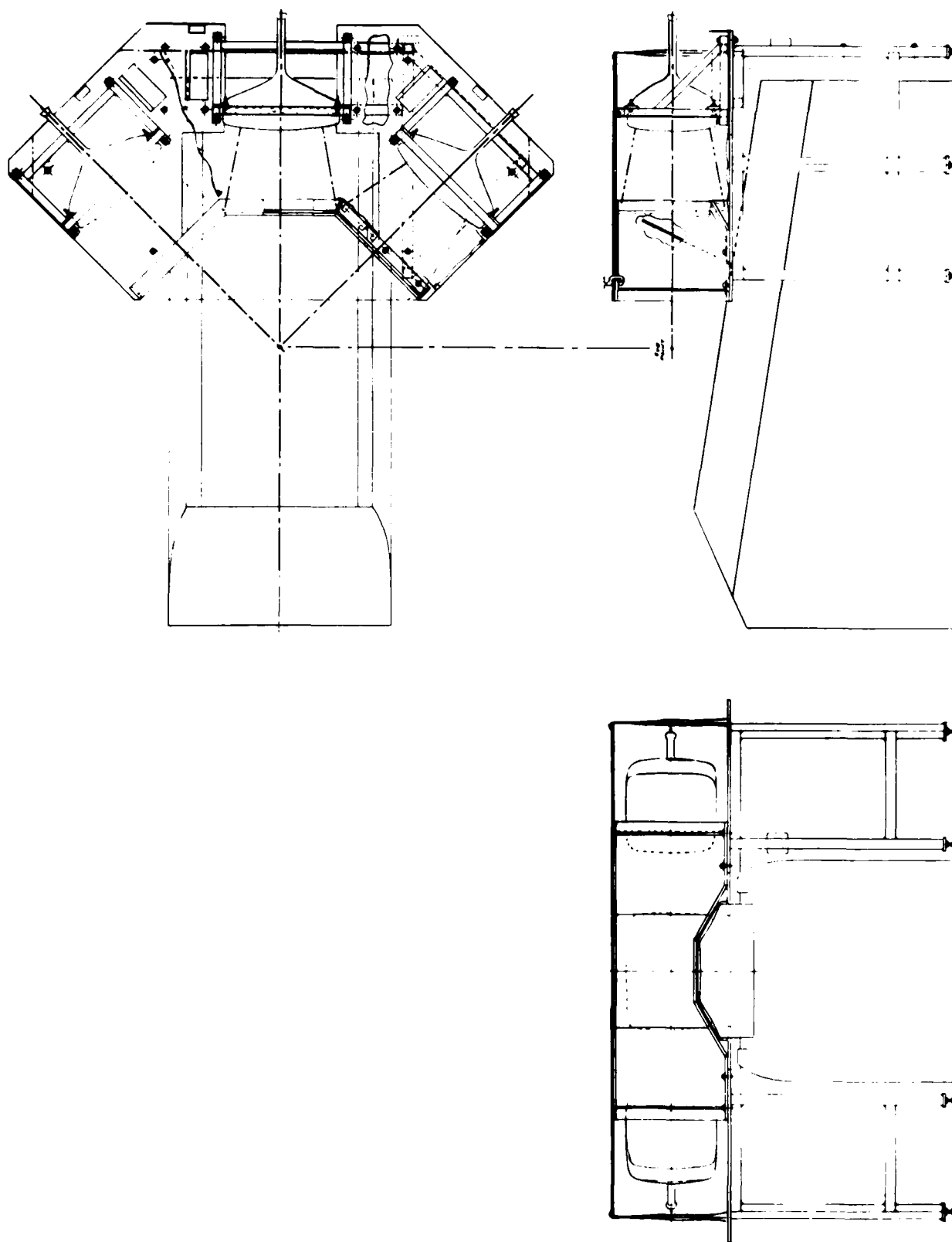


FIGURE 44 LAYOUT & ASSEMBLY (SUPPORT STRUCTURE, HOLOGRAPHIC WINDOW & CRT)

The total field-of-view is obtained as follows. Each window has an instantaneous FOV of 45° vertically by 50° horizontally, with the centers located 45° from each other. At the joints, there is a 5° overlap in the fields to allow for continuity of any observed images with observer head motion. The result is a continuous 140° horizontal field-of-view. Since the structure must accommodate a cockpit, the lower central portion has been cut out. The result is that the left and right windows have the required fields-of-view, but the center window is restricted to approximately 8° down field as against the nominal $22\frac{1}{2}^{\circ}$ for the left and right windows.

The framework is typical of structure used in the fabrication of a number of simulators produced in the past and consists of extruded aluminum members, welded to provide a lightweight, rigid assembly. The three holographic window modules are similar to conventional Pancake Windows except for the greatly reduced depth of the display collimating optics. Note that the elimination of the sagittal depth of the beamsplitter mirror, resulting from the use of its holographic counterpart, reduces the thickness of the Pancake Window sandwich to something on the order of $3/4$ ". The structure supports the Pancake Window, CRTs and associated electronics and mounts directly to the floor.

SECTION X
SYSTEM PERFORMANCE

Introduction

Upon completion of installation at WPAFB, the system was checked out, aligned, and set up for acceptance testing. The procedure followed is outlined in the Acceptance Test Procedure, (Appendix). This test plan encompasses all of the required specifications. It starts with component or sub-system tests, goes through a complete system demonstration, and concludes with a computer interface check-out and demonstration.

Sub-System Testing (Specification vs. Performance)

Terrain Model. The three-dimensional stationary, vertical, terrain model shall be detailed down to a level consistent with the overall system resolution and other requirements. The model shall have a minimum physical size of 15 feet vertical by 40 feet horizontal. Terrain shall be modeled at a nominal design goal factor of 2000:1, but the exact scale factor to be used will be determined during design reviews conducted by the contractor. The general model detail level and contents shall provide contrast, texture, natural and cultural features, and relief representative of models typically employed in commercial type camera/model image generators.

A visual inspection of the model satisfied all the cultural and size requirements. The following night lighting features were also satisfactorily demonstrated:

1. Strobe
2. Scene
3. Main Approach
4. Centerline
5. Touchdown
6. Runway 18L - 36R
7. Runway 15 - 33
8. Runway 33 Beacon
9. Taxi
10. Terminal
11. Main Runway

Gantry and Support. The gantry shall be capable of excursion consistent with the dimensions of the terrain model, the axes being defined as: X-axis: horizontal; Y-axis: vertical; Z-axis: normal to X-Y plane. Excursion in the Z-axis shall be a minimum of 24". Servo system performance shall meet the following minimums:

Positional Accuracy: Each axis better than 0.1% of full excursion.

Small Motion Response: Better than 0.002".

Frequency Response: 0.5 to 1 Hz.

Velocity: X-axis: 0 to 8 in/second
Y-axis: 0 to 5 in/second
Z-axis: 0 to 1 in/second

Acceleration: X-axis: 12 in/second/second
Y-axis: 6 in/second/second
Z-axis: 1 in/second/second

X-axis. All of the specifications relating to velocity, acceleration, frequency response, and excursion were satisfied.

The positional accuracy specification was not applicable since the fine position loop was not connected within the unit. Only the coarse loop functions in the position mode and does not have the accuracy to meet such a specification.

Since the X-axis is basically a velocity servo and is so operated in the system, the small motion response was also not applicable. Instead, smoothness of velocity about zero was satisfactorily demonstrated.

Y-axis. All of the specifications relating to velocity, acceleration, frequency response and excursion were satisfied. Positional accuracy and small motion response, for the same reasons as outlined for the X-axis, were similarly treated.

Z-axis. All of the specifications relating to velocity, acceleration, frequency response, small motion response, and positional accuracy were satisfied.

The excursion requirement of 24" cannot be met with the present system. The free travel of the Z-axis is limited (by the structure itself) to 17". Actual travel

(high altitude to touchdown is limited to approximately 9½". This latter restriction was a direct outcome of the probe/gantry/map model alignment procedure. During this effort, it was first required to make the probe's main optical axis (neglecting the scanning prism), be perpendicular to the X-Y plane of the gantry. Once this was established, it was only necessary to make the X-Y plane of the gantry parallel to the map model.

At this time, it was noted that the gantry had a slight pitch towards the model, resulting in a tilted gantry X-Y plane in respect to the model's plane. A further investigation showed that for structural stability, the gantry must have its upper roller lean against the guide rails. The system's problem introduced, however, was that the two planes were out of parallel by a significant amount. The bottom of the map model was then moved towards the gantry by approximately 4" to restore the required parallelism. This, plus the actual physical size of the probe, results in the total Z-axis excursion mentioned previously.

Illumination System. The terrain board shall be illuminated by a bank of lamps mounted on a sturdy framework. The type, number, arrangement, and spectral emission of the lamps shall be determined by the contractor so as to result in appropriate illumination at all points on the surface of the terrain board and to maximize response of the image pickup camera. Shadows caused by the camera carriage and gantry shall be illuminated by means of spot or make-up lamps which move with the camera carriage and gantry. Heat dissipation produced by the total sum of illumination lamps shall in no case exceed 150 kilowatts, with a desired total illumination lamp heat dissipation being 60 kilowatts or less.

The illumination system was demonstrated and found to meet all of the specifications. The item referring to shadows was covered by mounting a set of fill-in lights on the optical probe.

Optical Probe. An engineering feasibility model wide-angle optical probe shall be provided to the contractor as a Government furnished part, which the contractor shall mount on the gantry system. The contractor shall servo-mechanize the optical probe so as to meet the minimum performance specifications (Table 6).

1. All motors will be D.C. permanent magnet torquers/tachometers.
2. Feedback elements for pitch, yaw, roll, and yaw

TABLE 6
PERFORMANCE SPECIFICATION OF THE OPTICAL PROBE

Axis	Range	Maximum Velocity	Maximum Accel- eration	Velo- city Const. K	Position Repeat- ability	Minimum Smooth Velocity
Pitch	$\pm 25^\circ$	809/sec	809/sec ²	40	± 6 min	6 min/sec
Yaw	Cont.	809/sec	809/sec ²	40	± 6 min	6 min/sec
Roll	Cont.	1609/sec	1609/sec ²	40	± 6 min	6 min/sec
Yaw	Cont.	1609/sec	1609/sec ²	40	± 6 min	6 min/sec
Relay						
Tilt	0-15°	1.59/sec	69/sec ²	40	$\pm .1\%$	3 min/sec
Focus	0-12mm	1.8mm/sec	1.8mm/sec	40	$\pm .1\%$.1mm/sec

relay will be four wire resolvers, each geared 4:1 to the line of sight, i.e., one rotation of the line of sight will result in four rotations of the feedback element.

3. Values for tilt and focus are compatible with the dynamic and static requirements of both probe and mission profiles.

4. Feedback elements and multispeed requirements of tilt and focus will be a function of the requirements of (3) above.

The probe was tested, one axis at a time, and found to meet or exceed all of the specifications. Items labeled TBD were given values consistent with the probe requirements and tested to those assigned values.

There was only one exception taken during this on-site testing, and this refers to the question of repeatability. Although repeatability was measured and found acceptable at the contractor's facility, it was found impossible, due to probe accessibility and mounting, to get any meaningful measurements.

As for Note 1, in order to keep costs down to a minimum, 400Hz, two phase servomotor-generators from a similarly designed probe were used instead of the D.C. permanent magnet torquers/tachometers.

Video Processing and Control Equipment. The probe/camera/model/gantry image generator shall be equipped with electronic circuitry to provide generation of visual special effects of commercial type and capability in at least the following areas:

1. Ceiling control
2. Visibility control
3. Cloud top control
4. Day, dusk, dark control
5. Selective cultural lighting intensity control

An engineering feasibility model video processing system, required to interface the single channel high-resolution television camera on the model-gantry system with the multi-channel holographic display referenced in paragraph 4.1, shall be provided the contractor as a Government furnished part, and incorporated by him into the advanced visual system. This device is a video matrix generator employing a ramp timing method, with provisions for image overlap and switch-selectable video matrixing

to feed display mosaics varying from one-vertical by two-horizontal to two-vertical by four-horizontal.

The unit designed to perform all of the above requirements is as described in the section under "CLOSED CIRCUIT T.V. SYSTEM."

This unit was satisfactorily demonstrated and found to produce all of the required visual special effects.

Holographic Pancake WindowTM. The field-of-view of any one improved window shall depend on the curvature of the master mirror and the size of the CRT utilized in the display. The holographic window shall be configured to accept a 25" spherical faceplate CRT; in the event that such a 25" CRT is unavailable, the holographic window shall be configured to accept the 27" cathode ray tubes that are used in the SAAC display. In any case, the field-of-view of the display shall not be less than 45° vertical by 140° horizontal with three windows butted together.

A transit was positioned at the pilot's eye position, the CRTs illuminated with a cross-hatched pattern and measurements made on all three windows of the mosaic. The resulting fields-of-view of the windows are as follows (Table 7).

It should be noted that these angles are from a point, located at the pilot's eye position. However, the pilot with slight head motion, while still remaining within the pupil, can obtain the full 45° for each window (less the lower center window).

Transmission Efficiency and Uniformity of Brightness. The brightness of the collimated image shall be at least 1.0% of the brightness of the input image on-axis when viewed from the design eye point. The light level shall not vary more than 40% from the desired brightness anywhere in the window.

As measured on the windows in the actual system with CPTs in place supplying the illumination, the transmission of the center of the field is shown in Table 8.

The variation in brightness as measured across the three windows was well within the specified values and is listed in Table 9.

During the in-house system testing phase (prior to shipment to WPAFB), although the on-axis transmission using the narrow band P-44 CPT phosphors was nominally 1%, the

TABLE 7

FIELDS OF VIEW, HOLOGRAPHIC PANCAKE WINDOWTM

Left Window	43° - 40'H x 42° - 55'V
Center Window	44° - 25'H x 29° - 57'V*
Right Window	46° - 35'H x 43° - 12'V

* 22° -04' UP and 7° -53' DOWN

TABLE 8

HOLOGRAPHIC PANCAKE WINDOW TRANSMISSION

Left Window	-	0.37%
Center Window	-	0.39%
Right Window	-	0.40%

TABLE 9

VARIATION IN BRIGHTNESS

Left Window	-	33%
Center Window	-	33%
Right Window	-	21%

off axis transmission fell off too sharply. It was at this point that the change was made to the wider band phosphor. As a result, even though the transmission suffered, the brightness was more uniform.

Ghosts. The transmission of any single ghost image on-axis shall be less than 0.07% when viewed from the design eye point.

In making the ghost measurement, a black mask with an isosceles triangle cut out, was placed over the face of the illuminated CRT. The triangle was sufficiently displaced from the center to separate each non-infinity ghost image in order to avoid incorrect overlapping readings.

Four ghosts were immediately identified:

1. Direct view of the CRT, bleed-through or R (reject image) ghost.
2. Three inverted images, in front of the window increasing in size with distance from the window (R_2 , R_3 , and R_4 respectively).

Table 10 is a tabulation of the identifiable ghost images and their percentage transmission.

3. Collimation. As a design goal, collimation of the displayed image shall vary no more than 25 arc minutes when measured from the nominal eye position. When measured on-axis, each window had a collimation error within the specification. However, off-axis, each window's error increased to a nominal value of approximately 45 minutes.

4. Contrast. The system shall be capable of portraying at least 10 increasing brightness steps from black to white. A large area contrast ratio of 20:1 is a design goal.

When measurements were made on all three windows, each in turn exceeded the specifications noted above.

5. Color Balance. The basic color of the visual display should be primarily determined by the phosphor color of the input device. There shall be no gross color distortion introduced by the window optical color transmission characteristics.

All three CRTs were illuminated to their nominal brightness level and the colors of the window displays noted. The left and right windows appeared green, but

TABLE 10
GHOST IMAGE TRANSMISSION

Ghost Image	% Transmission		
	Left	Center	Right
R	0.045	0.03	0.024
R ₂	0.01	0.011	0.011
R ₃	0.013	0.006	0.004
R ₄	0.006	0.004	0.002

the center window appeared yellow. Measurements taken with a monochromator are listed in Table 11 for the window peak wavelength responses.

6. Blemishes. Every effort shall be made to prevent the inclusion of foreign material or air bubbles during the assembly of window components. However, it is recognized that certain of the materials used in the assembly have inherent manufacturing defects which may be visible. In any case, no blemish shall exceed 1/4" in diameter. Such blemishes do not include stains in coatings which are evident only under reflective light and which do not adversely affect performance.

The center window was relatively blemish free, however, the left and right windows showed "cement starts" at their edges which were greater than specified. The blemishes of the left window were confined to the left edge and those of the right window were confined to the right edge. The major portion of the central viewing area was therefore free of objectional blemishes.

Total System Testing

Technical Demonstration. The contractor shall demonstrate the performance of the 32" window and continuous view across the three windows at the conclusion of this effort. This shall include a test of those requirements in Section 4.0 of the statement of work.

To demonstrate the continuity of the view across the three windows, the following setup was made: A long fluorescent tube was calibrated with angular markings corresponding to the centers of the three windows at 0° and +45°, the overlap regions at +20° and +25°, and additional markings at +10°, +35°, and +55°. A line was also drawn along the length of the tube, crossing the angular markings at right angles. This tube was then set parallel to the gantry Y-axis, at a distance 24" from the probe's eye point and in the plane of the probe's X-Y axis. (The angular markings were calculated for a 24" distance between probe eye point and fluorescent tube face.)

When viewing this tube from the pilot's normal eye point, the observer now sees a continuous line, with the +20°, and +25° markings superimposed and fusing as seen through adjacent windows. As a further demonstration of continuity of field across the windows, a slow

TABLE 11

FINAL SPECTRAL RESPONSE OF
THE HOLOGRAPHIC PANCAKE WINDOWSTM

	Wavelength Response
Left	535-537 nanometers
Center	541-543 nanometers
Right	538-541 nanometers

continuous roll motion was introduced into the optical probe giving an "aircraft propeller" view. This further showed the merging of the views across all window seams.

The tube image was then positioned to appear horizontal across the focus of the three CRTs. Elevation was set to zero degrees. With a pocket transit set at the nominal eye point, the markings on the fluorescent tube were sighted and angles read. Table 12 shows the results of this test.

Computer Interfacing. The contractor shall have complete responsibility for providing the interfacing of the probe/ camera/model/gantry image generator and the holographic in-line infinity display with the STARS facility. The contractor shall thus determine, specify, procure, and install any signal-conditioning, buffering, and/or other interfacing circuitry, components, or devices required to result in a fully integrated visual simulation system.

The method used for computer integration was to check input/output signals between the computer and the equipment on a unit basis. For example, the "X" signal from the computer necessary to drive the gantry was first verified at the equipment interface and only then connected to the drive system. Similarly, the "X" position feedback signals were accounted for, both at the equipment output as well as at the computer "patch board" before actual connection into the system. In like manner, all of the 64 signal interfaces called for in the Interface Signals Document were thoroughly checked out with Air Force computer personnel.

TABLE 12. CONTINUITY OF FIELD OF VIEW ACROSS THE HOLOGRAPHIC PANCAKE WINDOWSTM

True Field	-55°	-45°	-35°	-25°	-20°	-10°	0°	+10°	+20°	+25°	+35°	+45°	+55°
Transit Readings	304°-18'	315°-05'	325°-28'	335°-10'	340°-12'	350°-02'	0°-00'	10°-00'	20°-00'	25°-08'	34°-40'	45°-08'	55°-14'
Angular Error	+42'	-5'	-28'	-10'	-12'	-2'	0	+5'	0	+8'	+10'	+8'	+14'

SECTION XI
SUGGESTION FOR SYSTEM IMPROVEMENT
AND RECOMMENDATIONS

Suggestions for System Improvement

System Defects. At the conclusion of installation, alignment and testing of the system, several defects became apparent. These had mainly to do with the images as seen through the holographic windows.

The most obvious defect was too little overlap of the views across the window seams. Even though the test data confirmed the fact that there was indeed a 5-degree overlap, very slight head motions exposed the dark or non-image areas between windows.

The second most noticeable fault had to do with image quality, namely, brightness and resolution. During system testing it was proved that the cameras provided high resolution video which could be substantiated merely by looking at the monitors. The problem was therefore in the CRT projection system. Even though it was not too apparent through the windows, by looking directly at the CRT's, a distortion of the raster was noticeable at the edges.

Reasons for Defects. During the design phase, the holographic windows were specified to have a focal length of 18.1". With this focal length, the remainder of the system design could proceed relatively independent of the window development. Therefore, a CRT raster size of 16.0" x 14.34" corresponding to a field of 50° horizontal x 45° vertical resulted. This also enabled the structure housing the windows and CRT displays to be designed and fabricated. When the holographic windows were fabricated and installed, it turned out that, instead of the 18.1" design focal length, the focal lengths were as shown in Table 13.

In addition to the focal length change, the optical centers of the windows were displaced from the geometric centers of the displays by approximately 1". To accommodate the increased focal lengths, each CRT display had to be

TABLE 13

FINAL FOCAL LENGTHS OF THE
HOLOGRAPHIC PANCAKE WINDOWSTM

	WINDOW		
	LEFT	CENTER	RIGHT
FOCAL LENGTH, (inches)	18.92	19.03	18.81

moved further away from the back of the windows. Unfortunately, not enough platform was left at the rear of the structure and the motion was limited to the small amount available.

Secondly, because of the lateral displacement of the window optical centers, the position of the rasters had to be moved to re-center the image as seen through the windows. With the CRTs further back, the raster size had to be increased in proportion to the increase in focal length, resulting in raster sizes of approximately 17" in width and 15" in height.

Two problems immediately arose:

1. The CRTs in their housings could not be moved laterally.
2. When displacing the raster horizontally to accomplish the same thing, distortion occurred at the edges, and in some cases the raster was off the edge of the tube.

The most expeditious choice at the time was to electronically reposition the raster since the resulting raster distortion would be confined to the edges of the field. It should be noted at this time that the maximum specified raster size, for proper system performance was 16.2" horizontally x 14.6" vertically. Increasing the raster size above these values resulted in a loss in resolution as well as in brightness. Furthermore, it placed undue strain on the high power drive electronics, which at times caused the displays to shut down due to overheating.

The loss of resolution was attributable to the reduction in video bandwidth of the display system. Originally, the video amplifiers were designed to a 30MHz bandwidth. However, as system testing was underway an unusually large number of CRT arcs were encountered. Even though some arc protection was installed, it was not sufficient to prevent damage to the drive electronics.

In order to keep the system "on the air," it was decided to increase by a factor of 4 the values of the series resistors connected between the video amplifier, and the G, and the cathode tube connections. Even though this showed a marked loss in bandwidth, it did stop the arcing problem, even though arcing still occurred. The final contribution to the loss in brightness was due to the inability of the CRT manufacturer to deliver a tube rated at the specified 800 ft-

lamberts. The delivered CRTs all averaged no more than 500 ft-lamberts.

Recommendations. The first step in improving the visual display is to replace the three holographic windows. Since the time the three original windows were manufactured, significant advances have been made in the development and production of high resolution holographic windows. With the installation of three new windows, each peaked to the same desired reconstruction wavelength, and having identical focal lengths of 18.1" and optical centers on the geometrical axis of the display, marked improvements in system performance can be started. Once the windows are in place, each CRT display can be re-centered and moved forward to the correct position consistent with the design focal length of the window. With the CRTs centered, their rasters then can also be centered, reduced to the correct size, and for the same system geometry (including 5° overlap) the net effect will be an increase in brightness and resolution.

To increase the overlap between adjacent windows, three possibilities must be considered; two require no re-design to the equipment, while the third requires a change in focal lengths of the windows and the probe's rear relay.

The first problem is to determine how much overlap is necessary. Restricting head motion to keep both eyes within the system's exit pupil, which is nominally 6" in diameter, the angle subtended from that eye position to the seam between adjacent windows can be determined. The center eye point position is 26" from the plane of the window and the angle from this point to the seam is 22½°. Moving this eye point 3" to one side increases this angle to 27.91°, which in the present system results in non-continuity of the scene. In fact, a displacement of only 1½" off center exposes the discontinuity. A design value of 11° overlap would then alleviate the problem.

In the first method to be considered, the horizontal raster size is limited to a maximum of 16.2". This corresponds to a maximum angle at the system eye point of:
 $\frac{16.2''}{16} \times 50^\circ$, or 50.63°. If the scanning format on the camera tube is not changed, it becomes quite obvious that the gain in the overlap region is only 0.63°. The second approach must then be considered.

In the second method, the camera tube is overscanned to increase the horizontal field angle. It should also be noted that in order to keep the same CRT raster size, the focal

lengths of the holographic windows must be shortened.

The camera sweep circuitry enables the raster to be varied in size by $\pm 5\%$. An increase in 5% of the horizontal field-of-view would increase the overlap region by only 2.52° . A discontinuity in the field of view for this situation would occur for a displacement from the centered eye position of only $1\frac{1}{2}''$.

The most practical alternative is then the third method of solution. In this method, both camera tube format and CRT raster are set to their nominal design values. Since new windows are recommended in any case, their focal lengths could be shortened to a value such that the total horizontal field-of-view for each display would be 56° . There would then be an 11° overlap at the seams of adjacent windows.

The focal length of the probe's rear relay would also have to be shortened to the same value as that selected for the windows. There would be some cutting out of the corners of the fields but not to the extent that it would be noticeable.

In respect to the problem of brightness and bandwidth (contrast), a better control of the CRT manufacturing process would yield a tube with less contamination and therefore less prone to arc-over. With such a new set of tubes, the brightness specification could be increased and the need for the brute-force arc protection lowered to a point where the inherent high video bandwidth of the display system is restored.

It has become apparent since the introduction of video disc machines that an alternative to image generation by means of model board and probe or CIG for certain limited applications might be feasible if certain fundamental obstacles could be overcome. This alternative incorporating one or more video disc machines should certainly be investigated under the current program aimed at a "Low Cost, Wide Angle Infinity Optics Visual System" because the cost of providing imagery by means of either a model or probe or CIG system would be reduced appreciably. The use of low cost video disc machines would, of course, limit the wide freedom of motion enjoyed by model board and probe systems as well as CIG systems. However, the low cost alternative could readily be applied to take-off and landing simulation as well as to weapon delivery simulation. The previously mentioned primary obstacle to the successful use of video disc machines involves the capability

of translating from one to any number of adjacent views stored on the video disc in order to provide translational freedom in flight so that one is not constrained in the visual "canned" mode.

The Farrand Optical Co., Inc. has recently overcome this barrier of translational freedom in a very simple and effective manner through the use of an analog computational device which does not resort to complicated digital processing of images.

We refer to this device as the Farrand Scenic Translator*.

* Patent Applied For

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